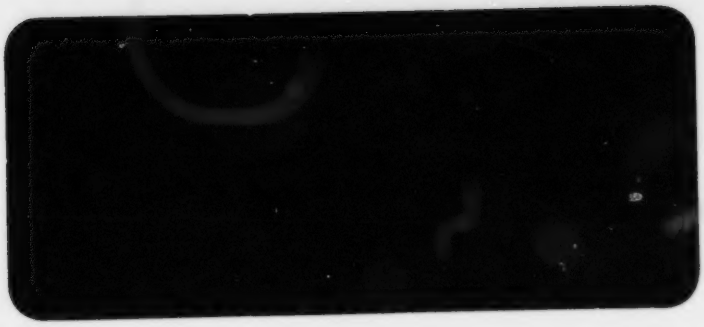


McINTYRE ENGINEERING
CONSULTANTS LTD.

CONTRACT REPORT NUMBER 79232-01-SQ
DSS REQUISITION NUMBER 23440-7-9232
CONTRACTOR: McINTYRE ENGINEERING
CONSULTANTS LTD.

BIOTECHNOLOGY FOR THE FOSSIL FUELS INDUSTRIES

- A PROPOSED FIVE YEAR RESEARCH AND DEVELOPMENT PROGRAM -

A Report to the Energy Research Laboratories/CANMET

MICROMEDIA

78pp

DSS 09SQ.23440-7-9232

89-05125/

BIOTECHNOLOGY FOR THE FOSSIL FUELS INDUSTRIES

- A PROPOSED FIVE YEAR R&D PROGRAM -

A Report to the

Energy Research Laboratories/CANMET

McINTYRE ENGINEERING CONSULTANTS LTD.
Ottawa, Ontario

March, 1989

DSS File No. 09SQ.23440-7-9232

MECL TWR.88-07

ACKNOWLEDGEMENTS

We wish to thank the Canadian corporate executives and researchers who participated in our survey. In the midst of falling oil prices and considerable scepticism over the role of federal government laboratories, these individuals had the foresight to recognize the potential benefits of judicious collaborative development of biotechnologies for fossil fuel production and utilization.

The interest expressed by industry is predicated totally on the excellent work performed in various academic, private sector and government laboratories across Canada, and abroad. We are most grateful to these researchers; in particular, Dr. T. Jack, Dr. R. McCready, Dr. W. Costerton and Dr. D. Westlake for establishing a base of Canadian expertise upon which the proposed program can build.

Research and engineering are international activities. We would like to express our gratitude to the twenty-two foreign researchers and executives who were willing to share their views on the potential opportunities afforded by microbial applications to hydrocarbon production and processing.

Finally, we would like to thank the Energy Research Laboratories of CANMET for the opportunity to undertake this work.

FOREWARD

Given the current state of downturn in the oil, coal and gas industries, the suggestion to embark on a long-term research and development program as presented in this report demands a high level of optimism and commitment to the continued development of this sector of our national economy. Novel and improved technologies will be required to meet changing feedstocks, new environmental regulations, modified product specifications, and shifting market demands. Biotechnology will address only a small fraction of industry's future technology requirements; however, the impact may be significant for some operations.

This report is only a brief overview of a very broad technical topic. It is presented as a springboard for direct discussions between industry, universities, BIOMINET, and the Energy Research Laboratories of CANMET. We would be most grateful for feedback and advice on any errors or omissions in substance or interpretation.

The views expressed in this report are those of the author, and do not necessarily represent the views of the Energy Research Laboratories or BIOMINET.

Mary-Jean Wightman, P.Eng.
McIntyre Engineering Consultants Ltd.
Ottawa, Ontario
January, 1989

SUMMARY

Canada's vast size and northern climate, and the standard of living afforded to its citizens results in our nation being dependent upon an assured, adequate supply of a variety of forms of energy. Our fossils fuel industries play a critical role in addressing this need. However, coal, oil and gas producers are facing long term challenges to their operations. Depleting conventional resources, degenerating feedstock qualities, low market prices for their products, increasingly stringent environmental regulations, and stiff market competition are demanding improved production efficiencies, tighter control of environmental emissions, lower production costs, and novel hydrocarbon upgrading techniques.

As is the case for other natural resource industries, fossil fuels producers are struggling to identify and master those technologies which will lead them successfully into the next millennium. Appropriate biotechnologies offer the potential to address some of these challenges. The greatest benefit will be derived from novel microbial technologies if they are optimally integrated with existing industrial practices, and hybridized with conducive physical and chemical unit operations. There are significant hurdles to be overcome before this integration can become a reality. The Energy Research Laboratories of CANMET can make a significant contribution to the search for commercially viable solutions by encouraging basic fossil fuels biotechnology research, and participating in the development of solutions to the biochemical and chemical engineering challenges associated with applying high technologies to low value, high volume natural resource-based products.

This report outlines a proposed strategy for the establishment and implementation of a Five Year Fossil Fuels Biotechnology Program. It is imperative that this program be developed by industry, universities and governments, collaboratively. Suggested areas of research and development to be supported through the Program include: enhanced oil recovery, in situ bitumen extraction; site remediation; basic biogeochemical and transport phenomena studies; bioconversion of natural gas; waste water and sludge treatment; sulphur processing; and, CO_2 removal.

A number of tactics are proposed to achieve these program objectives, including the establishment of the following:

- a fossil fuels branch of BIOMINET
- BIOMINET as a technical advisory committee to NSERC
- a Basic Research Fund
- a Proof of Concept Fund
- an Applied Research Fund
- an industrial R&D consortium.

The estimated cost of the federal government's share of this program, as proposed in this report, is $2.925 million over five years.

TABLE OF CONTENTS

SUMMARY i

INTRODUCTION

Background 1
Scope and Methodology 2

REVIEW OF THE TECHNOLOGIES

Introduction 4
Biogeochemistry 5
Enhanced Oil Recovery 6
Extraction of Bitumen from Oil Sands 16
Pipeline Transportation 16
Coal Bioprocessing 17
Bioconversion of Natural Gas (Methane) 18
Desulphurization 19
Coal desulphurization 19
Oil desulphurization 20
Gas desulphurization 21
Corrosion Inhibition 23
Environmental Emissions Management 23
Occupational Health and Safety 23
Catalyst Regeneration 24
Microbiological Prospecting 24
Summary of Sample Base Research Effort 24
Personnel 24
Focus of current activities 26

OPPORTUNITIES FOR APPLICATIONS IN CANADIAN INDUSTRY

Introduction 28
Light, Heavy, and Synthetic Crude Oils 29
Coal 32
Natural Gas 33

TABLE OF CONTENTS (Cont'd)

PROPOSED RESEARCH AND DEVELOPMENT PROGRAM

Introduction	34
Basic research element	36
Applied research element	37
Program infrastructure	40
Management	41
Budget	44

KEY PERFORMANCE INDICATORS 46

REFERENCES 47

APPENDIX A - List of Phase I Survey Participants (State-of-the-Art Technology Assessment)

APPENDIX B - List of Phase II Survey Participants (Industrial Technology Needs Assessment)

LIST OF FIGURES

Figure		Page
1	Schematic Diagram of Cyclic Microbial Enhanced Oil Recovery Process	10
2	Schematic Diagram of Microbial Flooding Enhanced Oil Recovery Process	11
3	Advertisement For Nippon Kokan's Bioreactor-Based H_2S Treatment System	22
4	Research and Development Employment Estimates For Sample Base	25
5	Summary of Research and Development Activities of Sample Base	26
6	List of Key Canadian Integrated Oil Companies	31
7	List of Key Canadian Oil and Gas Producers	31

INTRODUCTION

BACKGROUND

The Energy Research Laboratories (ERL) of the Canadian Centre for Mineral and Energy Technology (CANMET) are the sponsors of this report. On behalf of the Government of Canada, ERL undertakes commercially oriented research and development, and promotes the technological innovation of Canada's energy industries. Three general objectives of these activities are:

- to increase the productivity and enhance the competitiveness of Canada's coal, oil and natural gas industries
- to improve industrial health, safety and environmental control
- to support government policy initiatives for Canada's long term energy security.

In this context, ERL has been monitoring international research and development in the field of biotechnology pertaining to the fossil fuel industries (coal, oil and natural gas) for a number of years. ERL has financially supported six projects within this field. These projects were performed in Canada by universities, biotechnology companies and fossil fuel producers.

Bioprocessing techniques have been investigated in many countries for several decades. Some techniques are beginning to show evidence of substantial commercial relevance, and the rate of technological advancement is accelerating. This is happening at a time when Canada's fossil fuel industries are facing new or intensified challenges, including:

- the reduction of exploration, production and processing costs
- the recovery or extraction of unconventional hydrocarbon materials (heavy oils and bitumen)
- compliance with new product specifications (ex. lead, sulphur and aromatic concentrations)
- new market opportunities (ex. octane boosters, other natural gas products),
- while at the same time, minimizing any detrimental environmental impacts which may result from their manufacturing operations or the use of their products.

Prior to initiating consultative discussions with outside organizations regarding the possible establishment of a research and development program specifically aimed to stimulate the advancement of biotechnology applications for the fossil fuel industries, the Energy Research Laboratories commissioned this study by McIntyre Engineering Consultants. The purpose of this report is to present a synopsis of the state-of-the-art of biotechnology for the fossil fuel industries, and to present recommendations for the establishment and implementation of a collaborative industry/government/university program. This report will serve as a briefing document for the planned consultations.

SCOPE AND METHODOLOGY

The scope of work for this study focused on the Canadian fossil fuels industries; namely, oil, gas, coal and synthetic fuels producers. All facets of operation, from exploration to processing and refining, were considered. Associated issues such as transportation of feedstocks and products, environmental protection, and corrosion inhibition were also considered to be within the scope of work.

An evaluation of the current state-of-the-art of fossil fuels biotechnology was the starting point for this study. A literature and patent review of research and development in this field was performed. The methodology of the review is described later in this report. In addition, a survey of Canadian and foreign researchers working in the field of applied hydrocarbon microbiology was conducted to confirm and expand upon the information obtained from the literature review. A number of direct interviews were conducted to confirm findings from the survey.

In parallel to the technology evaluation, an assessment of the current industrial climate for the investigation and possible adoption of appropriate microbial technologies was undertaken. A survey of oil, gas and coal producing companies was the primary source of this information. Direct interviews with corporate executives were conducted to confirm and expand upon the information obtained from the survey. Key literature references on the topic were also reviewed.

As the National Biotechnology Network for the application of Biotechnology to Mining and Fossil Fuel Industry problems, BIOMINET sponsored the two surveys which were conducted as part of this project.

The outputs from the two parallel activities, the technology review and industrial climate assessment, were then compared to elucidate areas of common interest within the research and fossil fuel producing communities.

The common interests thus identified were used as the basis to develop a five year collaborative biotechnology research and development program.

A variety of models for the management of collaborative industry/university/government research and development were considered. Maximum industry participation and cross-sectoral networking were two primary objectives of the program management structure. The realities of integrating the proposed program into the 1987-1990 Energy Research Laboratories Strategic Plan were addressed.

REVIEW OF THE TECHNOLOGIES

INTRODUCTION

Referring to the original terms of reference, Phase I of the study required that a state-of-the-art review of fossil fuel-related biotechnological research and development be performed via a literature and patent search, and survey of key researchers in the field. Three distinct tactics were used to source the information required for this portion of the study:

- a literature and patent search to obtain the most recent references regarding biotechnologies for the fossil fuels industries
- a survey of senior research personnel within select Canadian and foreign companies
- direct interviews with some of the persons surveyed.

Methodology for the Literature and Patent Review

A comprehensive computerized search of the following databases was used to identify over 850 published references of research and developments related to biotechnology for fossil fuel production and utilization:

U.S. Department of Energy (DOE) [1983 to 1988],
World Patent Index [1968 to 1988], and
Claims/U.S.Patent [1950-1988].

The Survey Sample Base

Thirty-six private laboratories were invited to participate in this survey. Of these, seven are Canadian companies; twenty-three, American; and six are located in Europe and the United Kingdom. In addition, nineteen American public sector laboratories were approached to participate in the survey; along with fourteen Canadian public laboratories; and one each from France, the United Kingdom and the Netherlands. In most cases the contact was an active researcher in the field.

The original questionnaire circulation list was compiled from The MOSST Canadian Biotechnology Sourcebook, the Genetic Engineering News List of International Biotechnology Companies, Nickle's Canadian Oil Register, the Financial Post Survey of Industrials, the Research Centres Directory, the National Faculty Directory, press articles, and suggestions from other companies and researchers.

Of the seventy-two laboratories that received the questionnaire, thirty-two responded. The response rates were 58% for public sector laboratories and 36% for private laboratories. Six of the laboratories contacted are not actively engaged in biotechnology research and development for the production and utilization of fossil fuels; five of these laboratories are in Canada. One private sector laboratory did not complete the questionnaire for confidentiality reasons. In addition to the surveys, information was obtained from direct interviews with three private sector and three public sector researchers; one of these interviews was in lieu of completing the questionnaire. Two researchers withheld answers to sensitive questions for reasons of confidentiality. The effective sample base is twenty-five private and public research laboratories within Canada and abroad.

A list of survey participants is presented in Appendix A of this report.

BIOGEOCHEMISTRY

Bryant and Westlake have each reported that, while aerobic bacteria are known to biodegrade crude oil, there is no evidence in the literature which indicates that anaerobic microorganisms are able to initiate or readily decompose these hydrocarbons (15,21).

Oxygen concentration, temperature, pressure, and nutrient availability are key parameters influencing microbial hydrocarbon degradation. The order of biodegradation of specific components in hydrocarbons appears to begin consistently with the straight chain alkane compounds. The branched and aromatic hydrocarbons are then degraded, and the asphaltene and nitrogen and sulphur-containing compounds are generally the last to be biodegraded (15,21).

Physical properties such as pour point, viscosity, gravity, optical rotation and the physical state of oil (ie. dispersed, non-dispersed, or emulsified) can be affected by microbial activity. Prolonged microbial activity by mixed bacterial cultures, as would be observed under reservoir conditions, can result in the conversion of a fluid crude oil into a tar-like material such as is found in the Athabasca tar sands (21).

Biodegradation rates and results vary depending upon the type of crude oil substrate and the local reservoir environment. At lower concentrations, iron can stimulate biodegradation; whereas it acts as an inhibitor at higher concentrations (15). Marquis has reported the effect of high reservoir pressures on microbial growth and metabolism (20).

Careful design and laboratory testing of microbial formulations using reservoir fluids and preferably reservoir cores should be done prior to any MEOR field project. There are some microorganisms that grow very well under laboratory conditions, but do not mobilize residual oil in porous media studies (83).

The U.S. Electrical Power Research Institute (EPRI) has a number of projects covering the biogeochemistry of various microbial systems related to the commercial utilization of fossil fuels. Of particular note is the microbiological characterization of a manufactured gas plant site.

ENHANCED OIL RECOVERY

Enhanced Oil Recovery (EOR) is the practice of increasing the production rates or recoverable yields of an oil reservoir by injecting material(s) into one or more wells. The increased production is achieved through improved fluid mobility, reservoir sweep and/or conformance. Many different EOR techniques have been used, or proposed for use, in oil fields. These include solvent approaches using water, carbon dioxide or synthetic chemicals and, thermal approaches such as steam injection and fire flooding.

In general, microbiology will play a role in EOR processes in one of two ways. Either the microbes will be used in above ground facilities to produce biopolymers and biosurfactants for injection into wells, or the microbial cells will be injected directly into the reservoir for in situ production of cells and extracellular products. Due to the breadth of the topic, the former approach was not considered to fall within the scope of this report. Techniques that fall into the latter category are considered Microbial Enhanced Oil Recovery (MEOR) technologies. This latter topic constitutes a major subject of this report.

Microbially enhanced oil recovery has been defined by T. Jack, of Nova Husky Research Corp., as the use of microbial agents underground to facilitate, increase or extend production from an oil reservoir. Jack states that this is not a single technology based on a common approach; but rather, it is the adaptation of microbial systems to the specific problem of in situ oil recovery from a chosen target reservoir. Since the properties and composition of the reservoir and its contained fluids (oil, gas and water) can vary widely, MEOR technology is site specific. Using the following criteria: pH 4 to 8, temperature less than 75°C, and salinity below 10%, Clark et al. (1981) found that 50 +/-20% of the oil reservoirs in ten oil producing states in the U.S.A. would allow microbial growth (28).

After Zobell's initial work in the Forties, much laboratory research performed in the United States and Eastern Europe used *Clostridium*, and later, sulphate-reducing bacteria. The hydrogen sulphide production resulting from the latter eventually halted commercialization of these organisms for this use. A resurgence of interest in enhanced oil recovery in the Seventies triggered work in the United Kingdom, Australia, the Netherlands, the U.S.S.R.

and Canada, as well as in Eastern Europe (Poland, Hungary, Czechoslovakia and Romania) and the U.S.A. Reports on the historical development of MEOR technologies are abundant in the literature (13,17,18,55,80,101).

There are a number of different types of MEOR processes:

Selective plugging or filling of thief zones to precondition a reservoir prior to application of another EOR technique

The aim here is to inject cells into the formation via an injection well, allow them to accumulate in the higher permeability (thief) zones which do not contain substantial amounts of oil, and then trigger their growth and the in situ production of biopolymers by injecting a nutrient into the formation. After a certain amount of growth has occurred, the combined mass of cells and polymeric material results in selective plugging of the problem zones, thus facilitating subsequent mobilization of the more oil rich zones by other EOR techniques (water, polymer or CO_2 flooding). Jack and DiBlasio have proposed the use of *Leuconostoc* species for high permeability formations. Costerton and coworkers are pursuing the use of starved cells (ultramicrobacteria or umb) or spores for tighter formations. Ultramicrobacteria have smaller cell diameters (about 0.3 microns) than vegetative (growth) cells; spores have a more uniform cell surface. It is believed that these physical characteristics enable much deeper penetration of the cells into the reservoir formation. Their tendency to remain as singly dispersed cells under reservoir conditions avoids plugging of the injection well. Both Brown and McInerney have suggested the use of indigenous microflora in very low permeability formations (112,113). Each of these three approaches will be undergoing field tests in the near future (28,100).

Selective plugging to avoid watering out and coning

In this technique, microbes and nutrients are injected via the production well. Once in place within the formation, the microbes are triggered to produce extracellular polymers (polysaccharides) and, thereby, plug the water channels running through the formation to the well bore. This technique is especially suited for heavy oil production wells in which *watering out* is a common phenomenon (3).

Selective plugging may also be used to avoid water coning in producing oil wells by creating a local seal near the wellbore between the aquifer (lower water zone) and (higher) oil-bearing zone.

Mobility enhancement agents

Microorganisms produce organic acids, carbon dioxide, other gases, and other soluble fluids (biosurfactants, biopolymers, and bioemulsifiers) which may result in the same viscosity reduction and/or drive effects as achieved through the injection of synthetic polymers or CO_2. Another possible effect is the bioleaching of natural surfactants from the reservoir (or oil sands) hydrocarbons. There are two distinct methods of achieving mobility enhancement of the reservoir drive fluids:

1. **Repressurization**
   Jack has reported wellhead pressures increased to 700kPa due to gas formation during small scale fermentations in the field (33).

2. **Improved sweep efficiency**
   Sweep efficiency of waterflood secondary recovery processes can be improved by minimizing the viscous fingering effect of water channelling through the oil. This process is similar to polymer flooding in many respects. Gutnick reports that many biologically produced surfactants are extremely effective, and offer advantages over synthetic chemicals including: no toxic effects, high saline tolerance and tolerance to a broader range of temperatures. Possible mechanisms include alteration of both the interfacial tension between oil and water, and the wettability of the rock surfaces in the pore spaces of the formation treated (28,73).

Moses and Brown have suggested that in situ microbial polymer production may be more economic than polymer flooding with xanthan gum bioproduced above ground. Organisms to be used in this application must produce the desired metabolic products during a different life phase than the growth phase, otherwise the formation could eventually become plugged with cells. It is conceivable that such a product formation stage could be triggered by a modification to the microbial environment, as is currently practised in other industrial fermentations.

Biosurfactants are also used by companies such as Petrogen Inc. (Arlington Heights, Ill.) and others to recover oil trapped in sludge at the bottom of oil tanks.

Well bore cleaning

This technique involves the injection of bacteria (or other microorganisms) and nutrients into a production well. The well is then shut in until well head pressures rise, at which time the well is reopened. The acids, gases, solvents and surfactants produced by the microbes act to dissolve deposits (sand and clay particles, insoluble metallic scale, and tarry or waxy crude oil residues) between the casing and the formation. In some cases, the positive effects of microbial well bore cleaning have lasted up to several years. One product currently on the market contains microbes which selectively degrade higher molecular weight paraffins

often associated with well bore fouling during the production of waxy crudes. The cost of microbial well bore cleaning is low compared to alternative methods, and this approach has been suggested as potentially viable for the approximately 450,000 low volume individual stripper wells, which constitute a significant proportion of oil production in the United States (56).

Increase of carbonate reservoir permeability

In a manner similar to that of well bore cleaning, microbially produced organic acids are used in production wells to partially dissolve carbonaceous (limestone) formations, thereby increasing their permeability. Both well bore cleaning and the dissolution of formation carbonates may also be used in injection wells as a pretreatment to more elaborate EOR techniques (ex. CO_2 or polymer flooding).

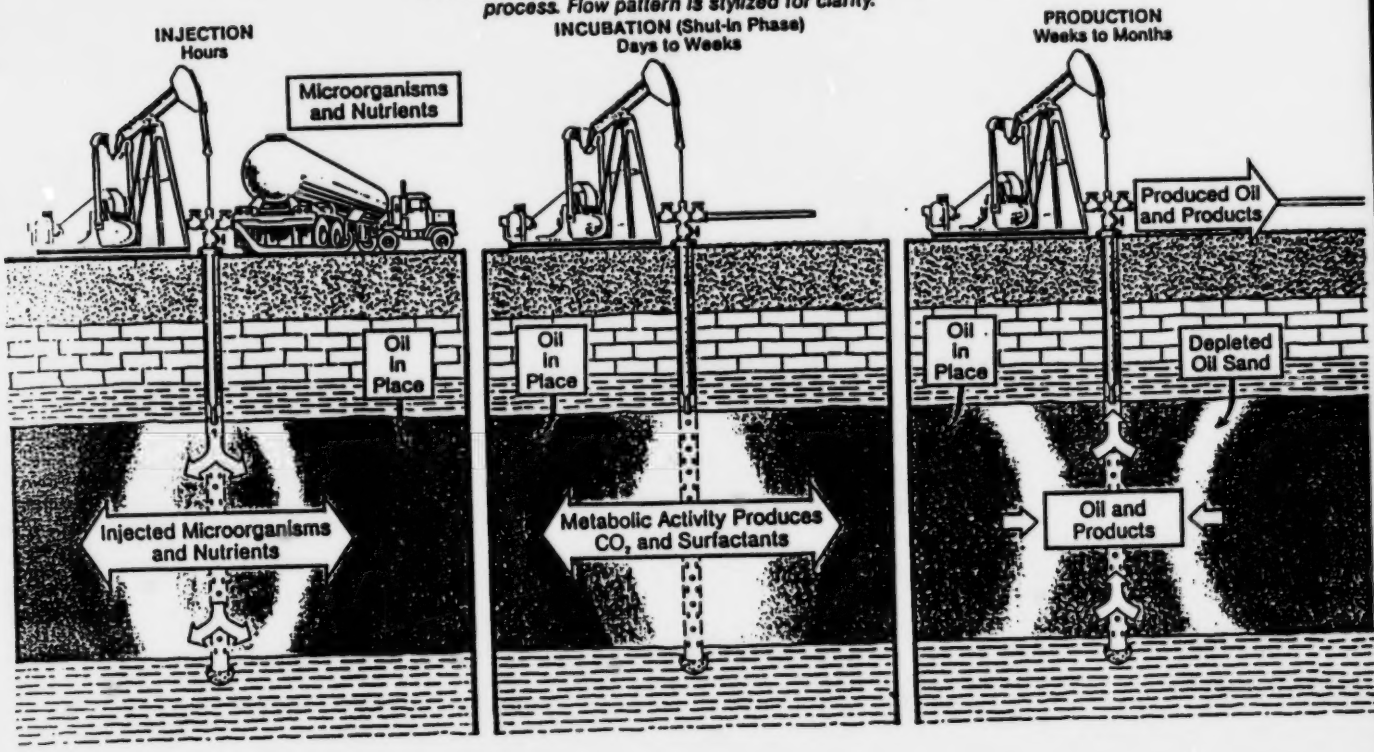
Figures 1 and 2 illustrate cyclic and line microbial enhanced oil recovery processes, respectively.

FIGURE 1

CYCLIC MICROBIAL RECOVERY

A solution of microorganisms and nutrients is introduced into an oil reservoir during injection. The injection well is then shut in for an incubation period allowing the microorganisms to produce carbon dioxide gas and surfactants that help to mobilize the oil. The well is then opened and oil and products resulting from the treatment are produced. This process may be repeated.

Schematic portrays one well during the 3 phases of this process. Flow pattern is stylized for clarity.

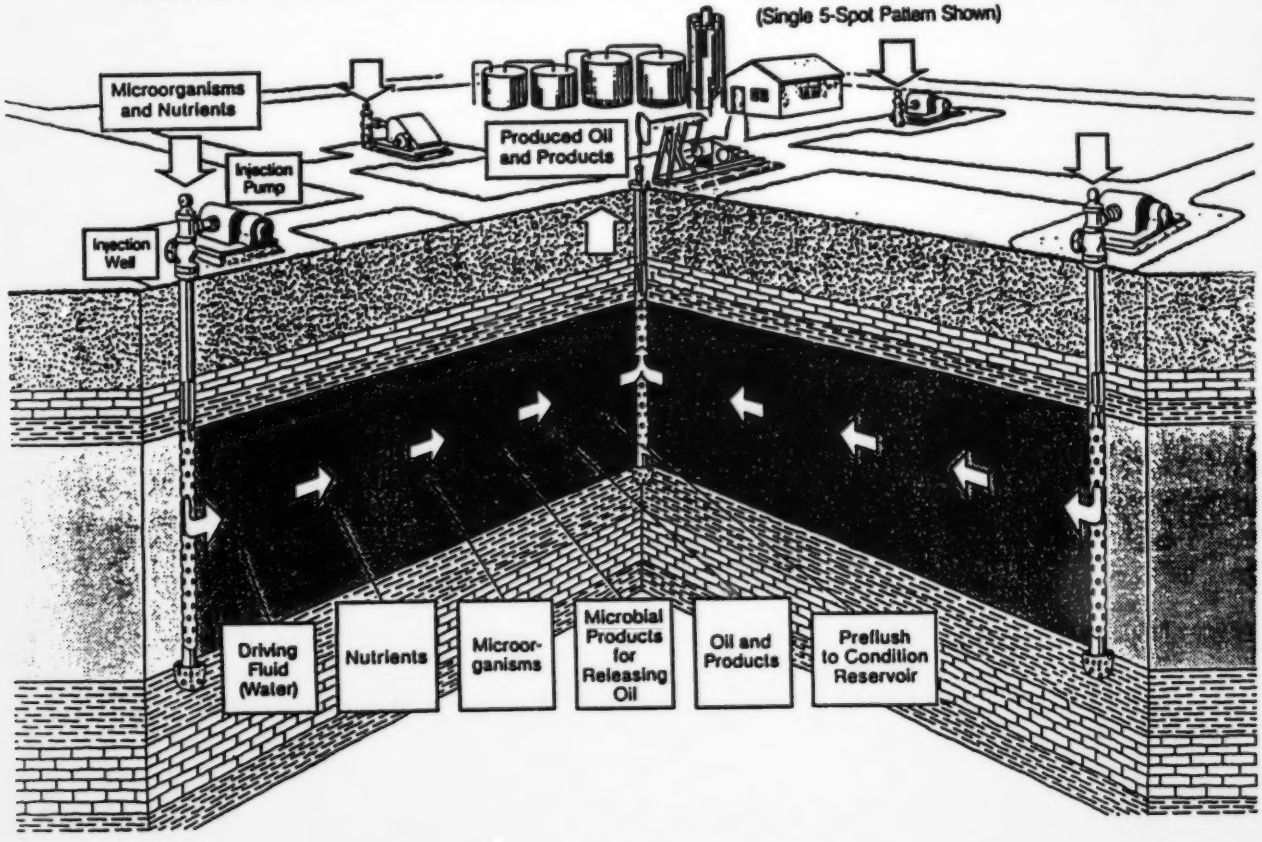


Source: Bryant and Douglas, Report No. Niper-138 (56)

FIGURE 2

MICROBIAL FLOODING

Recovery by this method utilizes the effect of microbial solutions on a reservoir. The reservoir is usually conditioned by a water preflush, then a solution of microorganisms and nutrients is injected. As this solution is pushed through the reservoir by drive water, it forms gases and surfactants that help to mobilize the oil. The resulting oil and product solution is then pumped out through production wells.



Source: Bryant and Douglas, Report No. Niper-138 (56)

In 1983, Jack reported the migration of injected microorganisms from one well site to an adjacent site, and a concomitant increase in oil recovery. This was taken as field evidence of the fact that it was the in situ microbial action, not the injection procedure itself, which stimulated oil production (28).

There is no risk of microbially degrading any significant portion of the oil within an MEOR target reservoir. This is based on the knowledge that there is no oxygen available to microorganisms that are injected into the reservoir and that, despite much investigation, no anaerobic cultures have been identified as being able to efficiently use hydrocarbons as a carbon source in the absence of oxygen. Hence, MEOR cultures are dependent upon a supply of injected nutrients. This suggests that exceptionally deep reservoirs or those requiring massive amounts of recovery agents are unsuitable for MEOR techniques (28).

The U.S. National Petroleum and Energy Research Institute (NIPER) has published a useful description of actual field MEOR operations. The procedures for injection of the microbial formulation and nutrient are similar to those used for well workovers to remove formation damage. For producing wells that are being pumped, the microbes and molasses are injected under gravity or with a gas-powered pump and flushed into the formation by injection of brine. A relatively small volume (ie. 0.5 to 5bbl) of microbial formulation, which is contained in drums, is injected. The molasses is usually transported to the field in a water tank truck and is diluted in the field with formation brine or injection water to a concentration of 2 to 10% and then injected into the formation. Brine is usually used to flush the molasses and microbes out into the formation. After a brief shut-in period of a few days to a few weeks, the well is returned to production (87).

In waterflooding projects, injection of microbes and nutrients into a relatively small project area can be accomplished through use of a simple bypass header. For larger-scale projects, installation of a centralized tank and injection lines for the nutrient is more cost effective (87).

Gas chromatography (GC) and liquid chromatography (LC) analyses of produced brine can be used to determine if chemical products from the microbial fermentation are propagating through the reservoir. Microbial analysis can be conducted to determine if the microbes are remaining viable in the formation (87).

Changes in oil and gas composition can also be an indicator of the performance of the microbial treatment. Alteration in bottoms, sediments and water (BS&W), and oil viscosity are frequently measured in single-well stimulation tests to determine if the injected microbes have survived in the formation and are affecting the composition of the crude oil (87).

According to Jack, the challenges to a successful field MEOR operation include:

- o getting the microbial inoculant into the formation at the desired location without plugging the injection well,
- o ensuring that the cells and nutrients arrive at the underground target site at the same time, and
- o achieving the desired cell dispersion through the formation.

While none of the challenges listed are insurmountable, careful preparatory investigations are required for each individual application in order to establish the best organism(s) and the most appropriate injection protocols for the particular application and site.

When the technology is appropriately applied, the economics of MEOR technologies can be very favourable. Molasses and cornsyrup are the most common nutrients, and pose low raw material costs. MEOR techniques do not require expensive modifications to existing field injection or production systems. Bryant and Douglas have suggested that the economics of MEOR are better than for other EOR projects. They estimate that a single-well MEOR test costs a few thousand dollars and that, given an increase in production from 2 to 5 bpd, the payback period would be two to three months. Refeeding could result in increased production for a year or more making it very cost effective (56).

Others have estimated the first well stimulation costs at about $13,300 U.S., and the treatment of subsequent wells at about $2,300 (24). There is little risk to the reservoir associated with the MEOR operation, and the potential improvement in production can be dramatic.

Most MEOR field tests to date have been batch operations on individual stripper or abandoned wells. Repeated feeding and continuous processes are now receiving more attention. More suitable reservoirs have not been made available for testing due to the lack of demonstrated control and predictability of MEOR processes. Dennis (Microbial Systems Corp.) has suggested the following MEOR site selection factors:

- operator cooperation
- site accessibility
- low brine salinity values
- established oil production decline curve
- established oil saturation
- reasonably uniform injectivity values
- favourable well spacing and pattern (or individual well)
- availability of historic and current project and reservoir data
- ability to isolate project site
- ability to easily measure incremental oil production increase
- compatibility with microbial inventory
- permeability above 50md (82).

Efforts are increasing to establish and disseminate test protocols (16,34,56,57,77,80,84).

Anaerobic and facultative anaerobic cultures are most often used in MEOR processes: *Clostridium, Bacillus, Pseudomonas, Leuconostoc.* Pre-conditioned proprietary mixed cultures are also used. At least one company (Alpha Environmental) is marketing an aerobic MEOR system which uses a natural liquid biocatalyst for in situ release of oxygen. It is suggested that the catalyst generates oxygen by splitting formation water. An enrichment media is also used in the system. The bacteria is preserved in dry powder form prior to use. This system has been designed to survive in brines up to 20 percent salt and temperatures up to 140°F. Carbonate formations show enhanced microbial effects. The cost is estimated at between $ 2,000 and $ 4,000 U.S. per well treated (27,85).

Hitzman has made two reports of MEOR field tests (13,80). A few observations are pertinent to the purposes of this report:

- Of seven Romanian reservoirs subjected to MEOR during 1975 to 1983, two were unsuitable for MEOR and should not have been tested; significant increases in oil production were reported for another two fields; and three fields recorded no significant effect. Some wells exhibited decreased production after the MEOR treatment. No explanation for this was offered. The increased production at the two reservoirs was maintained for periods of 7 to 8 months and five years. Repeated feedings were required to achieve this.

- An individual Canadian well field test experienced plugging of the formation in the well bore area due to lack of proper completion of the injection procedure because of bad weather conditions. The well was subsequently reperforated without difficulty. No permanent formation damage was evident and good fluid flows were reestablished.

- A 1954/55 test by Mobil in the U.S. resulted in the oil production from one well being increased from 0.6 bpd to 2.1 bpd over a six month period (also 23). In this case, the injected species (Clostridium) may have been overtaken by the indigenous microflora; nevertheless, the desired result of increased oil production via microbial stimulation was achieved.

- Micro-Bac Gulf Coast Inc. have reported a 1985/86 test in which their proprietary treatment was used to eliminate severe paraffin and formation skin problems. Production rose from 1.5 bpd of oil to 4 bpd in less than two months. No paraffin was visible after the treatment, and the wells which had previously required monthly servicing required no servicing after treatment.

- Microbial Systems Corp. recorded a 300% increase in water production (from 13 to 40 bpd) associated with a 230% increase in oil production (0.5 to 2 bpd) during a 1984 test.

Direct correlations between microbial activities and reservoir performance have not been conclusively established. Criteria upon which to predict the performance of an MEOR technology for a particular well site are not available. Hence, the technology is poorly understood by operating personnel and is not yet conducive to traditional engineering rigour. Furthermore, there are no standard assays, tests or calculations for the development of this core information. The National Institute for Petroleum and Energy Research (NIPER) in the U.S.A. has identified two issues related to MEOR that must be addressed before this technology can be fully exploited: efficacy and environmental impact assessment.

Laboratory testing and proper reservoir engineering design methodologies must be developed to ensure that the contamination of potable water aquifers, other sources of groundwater, surface waters, or agricultural land does not occur. Furthermore, the MEOR system must be designed to minimize the chances of survival and deleterious effects of any foreign microorganisms or mutations of injected populations which may arise. Laboratory tests should be performed to determine the compatibility of all injected fluids with reservoir fluids (both microbiological and chemical compatibility). Biocides should be kept available at the field site as a contingency measure (52,53,77).

NIPER is currently operating a carefully documented field trial of a semi-continuous injection of molasses into an inoculated waterflood (82).

Future MEOR studies should include identification of new organisms and nutrient media, and investigations of microbial compatibility protocols for field use. Such protocols should avoid competitive or subsequent growth of indigenous microflora which may result in detrimental effects to the reservoir, or the broader environment, and yet integrate with existing field procedures to the maximum extent possible. The current practice of treating injection waters with biocide will have to be addressed (22). Sulphate-reducing bacteria are of particular concern to operators. Studies of inhibitory and enhancing factors affecting microbial growth in reservoirs are required; as are investigations of the effects of pH and salinity on microbial survival under reservoir conditions. The behaviour and fate of bioproducts under reservoir conditions will also have to be determined.

The operator must be able to control the MEOR process. [Such a process must] *be able to tolerate redundancy and wastage* (29).

Genetic engineering is being applied to organisms for MEOR. The aim is to configure recombinant organisms for specific MEOR applications.

EXTRACTION OF BITUMEN FROM OIL SANDS

Extracellular bioproducts (enzymes, organic acids, biosurfactants and biopolymers) are of particular importance to both MEOR processes and related applications such as the enhanced extraction of bitumen from oil sands (2,5,8). Further development of these and new technologies may result in more economic and environmentally sound oil sands commercialization technologies.

Jack has reported that studies at the University of Western Ontario during the late Seventies identified a number of biosurfactants which improve the performance of primary separation processes for bitumen extraction (33). One of the most effective are corynemycolic acids produced by *Corynebacterium lepus*. Such bioproducts may improve the performance of existing oils sands recovery processes, and may also be applied to the emulsification of heavier crude oils and bitumen for pipeline transport (7). Others have suggested a possible cyclic huff and puff heavy oil emulsification MEOR process.

Jack states that *unfortunately the inability of bitumen to support anaerobic microbial growth suggests that the major opportunity for biotechnology in the in situ recovery area will be to provide biosurfactants or other chemicals for increasing the performance of other recovery technologies based on thermal or solvent processes* (33). He goes on to suggest that one such application is the use of dead bacterial cells as emulsion breaking agents, as discovered by Cooper and Zajic.

Methods of increasing the extracelluar yields of polysaccharides will be important in the further development of these technologies.

PIPELINE TRANSPORTATION

Biosurfactants are being developed and tested to facilitate the pipeline transport of heavy crude oils. The biosurfactants promote the formation of an oil-in-water emulsion with drastically reduced viscosities as compared to the crude oil alone. This could eliminate the need to use gas condensates, the supply of which is predicted to drop below demand by the early 1990's. The added benefit of increasing the effective pipeline capacity may be a secondary benefit resulting from this technology. It has been suggested by Jack and others that the emulsion would be easily broken on arrival at the refinery.

COAL BIOPROCESSING

Most of the literature on bioprocessing of coal is concerned with the removal of inorganic sulphur (pyrite). The removal of organic sulphur has been addressed in a number of recent references. Coal desulphurization is discussed in a later section of this report.

In addition to pyrite removal, *Thiobacillus ferrooxidans* removes a variety of metal-sulphide minerals from coal and fly ash. However, little research has been reported in this area (61,66,89).

Likewise, few references to the use of biosurfactants for coal slurrying (ie. coal solubilization) are found in the literature (61), although interest in this area is growing. EPRI has an active program in coal solubilization systems using *Penicillium* and *Coriolus versicolour* cultures (89). The Idaho National Engineering Laboratory uses an acid pretreatment (92).

The Institute of Gas Technology (IGT) is developing a combined process of solubilization and gasification of lignite to produce methane. The first stage involves an aerobic heap leaching process of alkaline oxidation and solubilization via fungal activity. The second stage is an anaerobic conversion (93). ARCTECH Inc. (Alexandria, Virginia) is also developing a two stage solubilization and gasification process. Their aim is to develop commercially viable conversions of low ranks coals (94). Another recent paper presents the bioproduction and purification of a fungal enzyme for coal solubilization (95).

In 1984, Ward, Egneus and Ellegard reported the apparent bioliquefaction of lignite by two wood decay fungi and the growth of a number of microorganisms on lignite leachates. *Polyporus versicolour* (a white rot fungi) and *Poria monticola* (a brown rot fungi) were identified. Coal bioliquefaction products are water- and methanol-soluble, highly oxygenated, structurally heterogenous compounds which appear to have a wide range of molecular weights (67). It has been suggested that the microbial processes involved may also have negative impacts on the commercial value and environmental integrity of exposed lignite coal (65,66). Researchers at Oak Ridge National Laboratory have identified seven different genera that extensively liquefy lignite and subbituminous coals. Other organisms have been identified by laboratories elsewhere in the United States and in Germany (67). Past difficulties in measuring the biodegradation of coal may now be alleviated by the use of diffuse-reflectance Fourier transform infrared analysis. Lignin, a cell wall polymer of wood fibre cells, can be used as a model for the evaluation of biological depolymerization of coal. There is an extensive body of literature available in the topic of lignin biodegradation (66).

According to Couch, many people believe that chemical pretreatment to breakdown the molecular structure of coal, making it more susceptible to microbial attack, is the best approach to bioprocessing (67).

Lushner and others have proposed the concept of a lignite refinery for the production of methane. Others have suggested in situ enhanced gasification of coal to methane (67).

With the complex processes likely to be associated with using coal as a (bioprocess) feedstock, a scale-up period of up to ten years is regarded as realistic (67).

BIOCONVERSION OF NATURAL GAS (METHANE)

A paper on this topic was presented by the IGT at their conference on Gas, Oil and Coal Biotechnology, December 5-7, 1988 (88). The authors suggest that a biological methane conversion product must have the following characteristics to compete with synthetic chemicals:

- one or more chiral centres
- value-added ratio greater than one, where this ratio is measured as:

$$\left\{\frac{\text{value of product - value of substrate}}{\text{value of substrate}}\right\}$$

- high conversion yield
- economical recovery
- large total income
- no environmental or safety concerns.

IGT's future work will concentrate on higher price chemicals which can be produced stereospecifically by a biocatalytic co-oxidation process. Methane-utilizing microorganisms will act as, or produce, the biocatalyst.

At the same conference, EPRI reported that they are investigating the use of metallo-porphoryins and multiple non-porphoryin manganese complexes as biomimetic catalysts for the conversion of methane to methanol.

The University of Minnesota presented studies of the biochemistry of the bacterial oxidation of methane. In their work, they offer a new purification strategy for the bacterial methane monooxygenase enzyme (97). In a related presentation, the University also presented a paper on the genetic and biochemical studies of methylotrophic bacteria (98).

Research performed at the University of Arkansas is aimed at developing a biological conversion process for coal synthesis gas. Two organisms have received special attention: *P. productus* (which produces acetate) and *Methanothrix sp.* (which converts acetate to methane). Both mixed reactors and immobilized cell reactors have achieved total carbon monoxide and hydrogen conversion in retention times of less than two hours. These are relatively high reaction rates for a biological process (74,96). No other references on this topic were found in the literature. Another group at the same university is studying bioreactor design for gaseous substrate fermentations (99).

DESULPHURIZATION

Coal Desulphurization

Investigations into the microbial desulphurization of coal first began over thirty years ago. Modern interest has been stimulated by tighter environmental emissions control regulations aimed to curb acid rain. There are two basic approaches: ground coal processing and heap leaching. Most research has focused on the former, whereas the latter process seems to be more relevant to current industrial practice. Heap bioleaching is also the process used to bioleach uranium and copper. Heap bioleaching accounts for between 10 and 20% of uranium and copper production in the United States. Uranium bioleaching is also used commercially in Canada and the U.S.S.R.

One drawback to much of the research undertaken to desulphurize coal was the emphasis on pyritic (inorganic) sulphur. Inorganic sulphur can account for only as much as 50% of the sulphur found in most coals. While up to 90% of this material is removed by microbial means, reaction rates are slow and effluent processing may be required (46 and others).

Economic analyses have been performed for a number of possible bioprocesses for pyrite removal (67,11,44). Estimates fall in the range of $ 12 to 20 U.S. per tonne of coal treated. It is suggested that these costs are lower than those associated with other desulphurization process: TRW ferric leaching (Myers) process, Battelle hydrothermal process, Kennecott O_2 leaching process, and solvent refined coal (67,11,45).

More recently, reports of laboratory scale processes which remove up to 90% of the organic sulphur have been recorded (4,40,43,64,66,67,91). Current chemical and physical methods cannot achieve this level of desulphurization. The literature is contradictory on whether fuel values are affected by organic sulphur removal. IGT claims their newly isolated mixed bacterial culture (IGTS7) is unique in its sulphur-specific metabolism. Standard Oil, Atlantic Research, the Institute of Gas Technology, Dynatech Scientific Inc. (Cambridge, Mass.) and others are working in this area. Research is underway in the U.K., U.S., Netherlands, West Germany, India, Turkey, and Eastern Bloc nations. The most commonly used organisms are mesophilic: *Thiobacillus ferrooxidans, Thiobacillus thiooxidans, Sulpholobus acidocaldarius* and a *Pseudomonas* (Atlantic Research's Coal Bug 1 or CB1). Reaction rates are currently too low for commercialization. EPRI and others are investigating the use of thermophilic bacteria (*Pyrodictium brockii* and *Pyrococcus furiosus*). The higher allowable temperature may increase reaction rates, thereby reducing required retention times and, therefore, reactor size (89). Genetic engineering is considered to be a likely route to viable process development.

The size of bioreactors required for coal desulphurization would have to be reduced if commercialization of these technologies is ever to occur (12,45). Kargi has suggested that a shallow pond configuration (typical depth of 0.2m) aerated and agitated by surface mechanisms in a controlled environment on the site of a power plant is the most appropriate type of reactor (44).

Other processing configurations enable the integration of microbial processing with other coal preparation processes or waste coal reclamation methods. It has been suggested that coal desulphurization be combined with coal slurry transport (4,63). Heap leaching, a process already used commercially to extract uranium and copper, is another alternative. In 1985, McCready and Zentilli showed that bacterial heap leaching could remove pyrite and qualitative amounts of environmentally undesirable trace metals from coal if such a process were developed for waste coal reclamation (72). Others have also reported on this method (67). Beyer recently reported on a percolation bioreactor (41).

There is also a potential to combine physical separation and desulphurization processes (67). McCready and coworkers hold a Canadian patent for the *Bioadsorption Alteration of Iron Sulphide Surfaces* (6). Given between fifteen and sixty minutes of contact time, this process renders the sulphide surfaces adequately hydrophillic for separation by conventional means (agglomeration, flotation or adsorption). The mechanism is the adsorption of iron-starved *T. ferrooxidans* to pyrite in finely ground coal. Attia and Elzeky reported a 40% reduction in pyrite flotation after less than 15 minutes of bacterial pre-conditioning. Other groups have reported even shorter pretreatment times (67). Based on recent findings by the U.S. Department of Energy's Pittsburg Energy Technology Centre, surface modification seems to be the most promising approach to commercial coal desulphurization. The DOE found that selective agglomeration, liquid cycloning or advanced froth flotation could each reduce emissions from moderate-sulphur coals below the expected new limit of 1.2 lb of sulphur dioxide per million BTU at costs of about half that of limestone flue gas scrubbing (62).

As secondary benefits, desulphurization seems to have a positive effect on ash formation and subsequent heat transfer efficiencies.

Oil Desulphurization

A significant portion of the sulphur contained in heavy oils and bitumen is present as aromatic sulphur compounds containing a thiophene ring. Such compounds can be partially oxidized by microbial action. The bioenzymes used in this oxidation process might one day be used to desulphurize these reserves.

Jack has reported that the desulphurization of conventional sulphur bearing crudes has been demonstrated but that the resultant process would yield a large waste stream of partially oxidized sulphur containing aromatics. No economic method of processing of this waste stream has been identified to date. Even partial biodesulphurization of asphaltenes has not yet been proven (33).

Gas Desulphurization

Hydrogen sulphide (H_2S) is extremely toxic and highly corrosive. As such, the removal of H_2S from natural gas, synthetic gas, refinery offgases, biogas and other industrial gas streams is of major importance. Microbial desulphurization of these gas streams has the potential to offer a more economical process than current industrial practices. The economic advantage is due, at least in part, to the milder reaction conditions and high reaction rates of the microbial process.

K. Sublette has performed the majority of work reported in the literature regarding the desulphurization of hydrogen sulphide, and, more recently, sulphur dioxide (via the hydrogen sulphide oxidative route). His work is sponsored by Combustion Engineering Inc. (Windsor, Conn.) or its subsidiary, Lummus Crest Inc. (1).

The anaerobic microbial system can treat the tail gas from a Claus process. Alternatively, if the treated gas has no fuel value, then an aerobic oxidation system could replace the conventional Claus process and tail gas clean-up system. The system does not require aseptic conditions. The bioreaction products are biomass (a single cell protein product) and a sulphate salt (36,59).

The technology developed by Sublette uses *Thiobacillus denitrificans* in a sulphur-limited oxidation of H_2S. More recently an immobilized culture has been developed which combines *Thiobacillus denitrificans* with floc-forming heterotrophs to produce a macroscopic floc with excellent settling properties (60).

While Combustion Engineering does yet offer Sublette's technology as a commercial process, Nippon Kokan (NKK) is marketing a *unique bioreactor-based H_2S treatment system that turns sour gas sweet* (see Figure 3, next page). NKK's aerobic process uses *Thiobacillus ferrooxidans.*

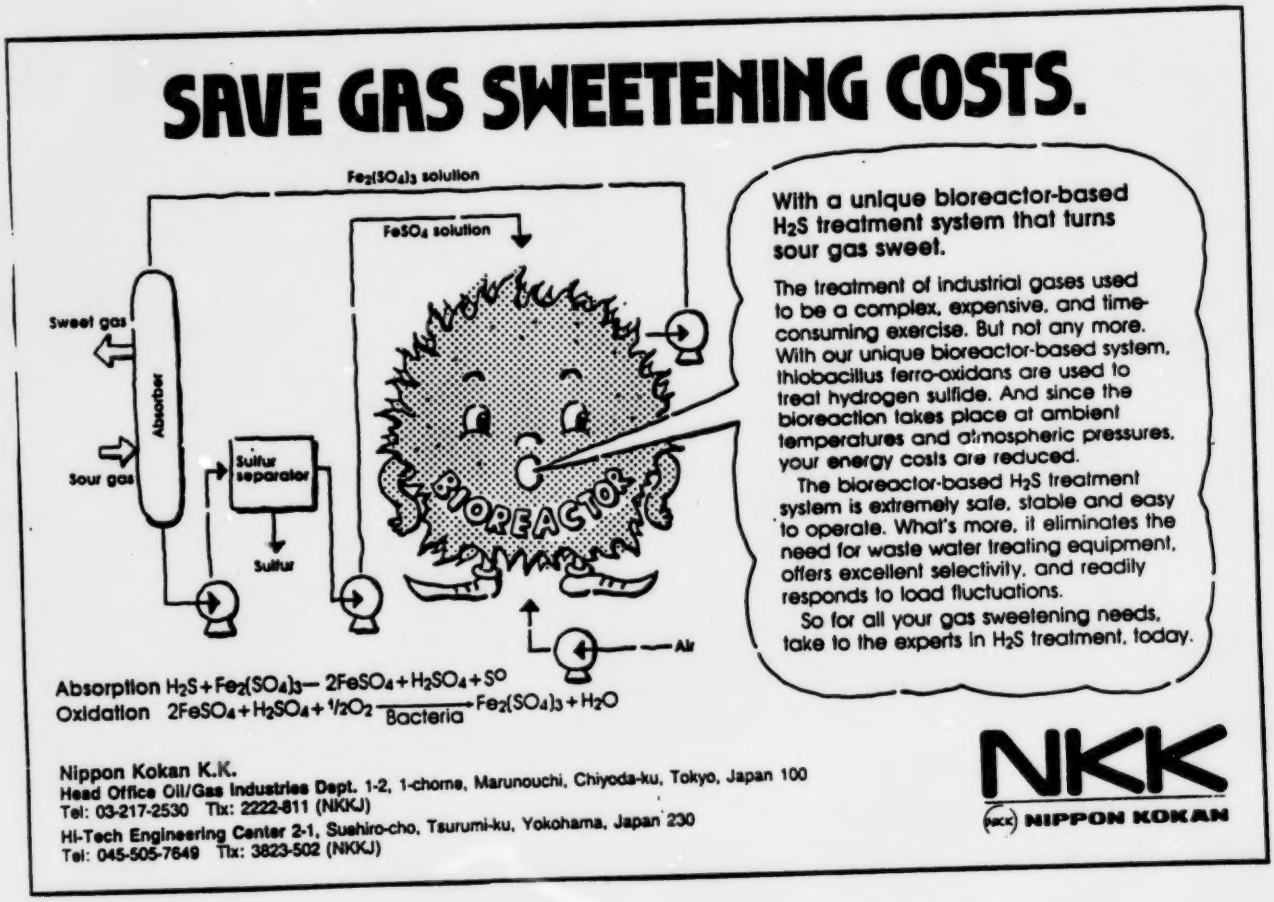

SAVE GAS SWEETENING COSTS.
$Fe_2(SO_4)_3$ solution
$FeSO_4$ solution
Sweet gas
Absorber
Sour gas
Sulfur separator
Sulfur
BIOREACTOR
Air
With a unique bioreactor-based H_2S treatment system that turns sour gas sweet.
The treatment of industrial gases used to be a complex, expensive, and time-consuming exercise. But not any more. With our unique bioreactor-based system, thiobacillus ferro-oxidans are used to treat hydrogen sulfide. And since the bioreaction takes place at ambient temperatures and atmospheric pressures, your energy costs are reduced.
The bioreactor-based H_2S treatment system is extremely safe, stable and easy to operate. What's more, it eliminates the need for waste water treating equipment, offers excellent selectivity, and readily responds to load fluctuations.
So for all your gas sweetening needs, take to the experts in H_2S treatment, today.
Absorption $H_2S + Fe_2(SO_4)_3 \rightarrow 2FeSO_4 + H_2SO_4 + S^0$
Oxidation $2FeSO_4 + H_2SO_4 + 1/2O_2 \xrightarrow{Bacteria} Fe_2(SO_4)_3 + H_2O$
Nippon Kokan K.K.
Head Office Oil/Gas Industries Dept. 1-2, 1-chome, Marunouchi, Chiyoda-ku, Tokyo, Japan 100
Tel: 03-217-2530 Tlx: 2222-811 (NKKJ)
Hi-Tech Engineering Center 2-1, Suehiro-cho, Tsurumi-ku, Yokohama, Japan 230
Tel: 045-505-7649 Tlx: 3823-502 (NKKJ)
NKK
NIPPON KOKAN

Figure 3. Advertisement for Nippon Kokan's Bioreactor-Based H_2S Treatment System

Source: Chemical Engineering, April 11, 1988, p.78.

CORROSION INHIBITION

Molecular probes are being developed and commercially used to detect the presence of sulphate-reducing bacteria (SRBs) in oilfield fluids. Under anaerobic conditions, SRBs can cause microbial corrosion of drilling and gathering systems. Waterflood enhanced oil recovery operations are particularly vulnerable to this phenomenon. SRBs have also been reported responsible for the souring of crude reserves. A number of companies are commercializing this technology.

ENVIRONMENTAL EMISSIONS MANAGEMENT
(See also Desulphurization)

Nova Husky Research Corp. has developed methods to accelerate the conventional land farming process so as to minimize the environmental impact of this practice. Dr. M. Francis is working in this area.

Soil reclamation (bioremediation) technologies are being developed and applied in the private sector. At least two Canadian firms are known to be working in this area (Dearborn Environmental and Lavalin). American firms in this business include Biota (Los Angeles), Detox Industries (Sugar Land, Texas), Biprocess Engineering (Wilmington, Del.), Remediation Technologies Inc. (104) and Zimpro Environmental Control Systems (Rothschild, Wis.). IGT and the University of Tennessee are each working to establish protocols and design procedures for soil treatment and enhancements to current practices (103, 105). EPRI is actively investigating genetic engineering techniques for this application. In general, the technology employed for soil reclamation is an active type of land farming wherein the contaminated soil is inoculated with selected organisms and nutrients, and the biodegradation of the toxins is monitored and promoted. Processing costs can be significantly lower than shipping to a landfill site (69).

Waste water treatment bioprocesses (including oil sludge treatment) are being developed by a number of laboratories. Combustion Engineering Environmental (Portland, Maine) uses white rot fungi in rotating biological contactors to degrade hazardous wastes. CANMET's Mineral Sciences Laboratories are using similar equipment for mineral bioprocessing.

The U.S. Electric Power Research Institute is studying the potential of modern biotechnologies to achieve a reduction in carbon dioxide emissions, thereby hopefully alleviating the greenhouse effect (90).

OCCUPATIONAL HEALTH AND SAFETY

On Canada's East Coast, the use of methylotrophs to stabilize coal storage by consuming explosive methane gas is being investigated.

REVIEW OF THE TECHNOLOGIES

CATALYST REGENERATION

The Georgia Tech Research Institute holds a 1985 U.S. patent for removal of inorganic contaminants from catalysts (10). Inventors Myerson and Ernst used *Thiobacillus ferrooxidans* to remove vanadium and nickel from a spent cobalt-molybdenum (hydrotreating) catalyst. Hydrocracking catalyst (silica-alumina zeolite) can also be processed in this manner. The metal contaminants are reduced to less than 0.001 wgt.% and are removed even from the catalyst pores. The regenerated catalyst can be reused, and the recovered metal impurities can be processed for commercial reuse. This was the only reference to bioregeneration of spent catalysts found in the literature.

MICROBIOLOGICAL PROSPECTING

No English text references to the application of microbiology to prospecting for natural gas and crude oil deposits were found during the literature searches undertaken for this study. A couple of articles on geochemical exploration technologies referred to microbiological prospecting. However the only actual reference found on this topic was a 50 page article published in Polish in 1970 (111). Two foreign researchers listed microbial prospecting as one of their areas of research and development interest; no Canadian researchers indicated activity in this area.

SUMMARY OF SAMPLE BASE RESEARCH EFFORT

Personnel

An estimate of the numbers of scientific and technical persons employed in biotechnology research and development related to the production and utilization of fossil fuels has been determined from the responses to the Phase I survey.

In total, the nine respondent laboratories within Canada's public sector employ approximately 25 persons in the field of biotechnology for the production and utilization of fossil fuels. Roughly half of these researchers have a doctorate degree, with the remainder split evenly between Master and Bachelor levels. The majority of them are employed as full-time researchers; although many also perform research activities in other application areas, and carry-out teaching responsibilities.

In total, the four Canadian private industrial laboratories which responded to our survey employ about a dozen scientists and technicians in this field. The distribution according to academic qualifications is similar to that in the Canadian public sector in that roughly half those employed have a doctorate degree. Most of the remaining individuals are at the Master's level. With a few exceptions, they are all employed full-time.

Eleven foreign public sector laboratories, employing a total of eighty-five researchers, responded to our survey. Forty-one individuals were reported as being employed full-time; sixteen, part-time; eighteen, contract; and, ten on academic postings.

The eight foreign companies who responded to our survey reported a total of ten researchers in this field, most of whom are employed full-time.

Figure 4 presents these employment estimates for the sample base sectors, both within and outside of Canada, by academic qualifications and by term of employment.

Figure 4. Employment Estimates for Sample Base

	Canadian		Foreign	
	Public	Private	Public	Private
Post Doctorate	10	3	20	--
PhD	4	3	21	4
MSc	5	4	15	2
BSc	4	1	26	4
Diploma	1	0	3	--
Total	24	11	85	10
Full-Time	17	10	41	7
Part-Time	--	1	16	--
Contract	2	1	18	1
Academic Post	4	--	10	2
Total	23	12	85	10

Source: MECL 1988 Survey
(Note: Differences in totals within the same column are as reported by survey participants.)

The relative size of foreign private sector efforts are not accurately reflected by these results. A lack of incentive to respond to our survey, and proprietary restrictions, precluded response from a number of companies outside of Canada. Furthermore, only a fraction of the identified foreign firms working in this area were contacted. Hence, these results do not contradict the general (and reasonably expected) observation that there is much more industrial research and development underway in this field outside of Canada, than within Canadian firms.

Focus of Current Activities

Figure 5. Summarized Activities of Sample Base According to Number of Reporting Laboratories

	Canadian		Foreign	
	Public	Private	Public	Private
OIL				
Microbial Enhanced Oil Recovery	--	--	4	--
repressurization	2	2	5	3
mobility agents	2	1	4	--
selective plugging agents	1	1	4	--
well bore cleaning				1
associated genetic engineering techniques	--	--	--	--
souring prevention	1	--	--	
Bitumen Extraction				1
from oil sands	1	--	4	1
from oil shales	--	--	4	3
Desulphurization of Oil	1	1	1	2
Denitrification of Oil	--	--	5	2
Biodegrading of Oil	1	4	--	1
Demetallization of Oil	--	--	--	--
Residue Utilization	1	--	--	1
Heavy Oil Viscosity Reduction	--	--		
Bioconversion	--	1	--	--
of ethylene	1	1	2	
other				
COAL			5	2
Desulphurization of Coal	--	--		
Coal Surface Modifiers (incl. Biosolubilization)	1	1	4	1
Biodegrading of Coal	--	--	5	--
Upgrading of Coal-Derived Synthesis Gas	--	--	2	1
Demethanization of Coal Gas	--	1	--	--
Other Coal Environ. Concerns	--	--	1	--

Figure 5. Summarized Activities of Sample Base According to Number of Reporting Laboratories (Cont'd)

	Canadian		Foreign	
	Public	Private	Public	Private
ENVIRONMENTAL				
Wastewater Treatment				
Boiler Feed Water	--	--	--	--
Cooling Water	--	2	--	--
Waste Waters	2	2	4	2
Flue Gas Scrubbing	--	1	1	1
Soil Reclamation	1	3	1	2
GAS				
Desulphurization of Nat. Gas	--	1	1	1
OTHER				
Dewatering of Peat	2	--	--	--
Corrosion Inhibition	1	2	2	--
Biogeochemistry	1	--	--	--
Microbial Prospecting	--	--	2	--

OPPORTUNITIES FOR APPLICATION IN CANADIAN INDUSTRY

INTRODUCTION

Referring to the original terms of reference, Phase II of the study required that major current and anticipated problems and challenges to the Canadian fossil fuels industries be identified. Three distinct tactics were used to source the information required for this portion of the study:

- a literature search to obtain the most recent reviews of the technical challenges facing Canadian coal, oil and gas operating companies
- a survey of senior research and operations personnel within these industries
- direct interviews with some of the persons surveyed.

As the aim of the study was to develop a collaborative industry/university/government research and development program, corporate personnel were also asked questions regarding preferred methods of research and development collaboration.

The Survey Sample Base

Fifty-eight Canadian companies were invited to participate in this survey. Of these, the vast majority were operating coal, oil or gas firms; a few consulting firms were included with this group. In most cases, the company contact was a senior executive. Thirteen Canadian industrial associations and government-supported organizations were also approached to participate in the survey, along with one American association, and one international association based in Europe.

The original questionnaire circulation list was compiled from Nickle's Canadian Oil Register, the Financial Post Survey of Industrials, Standard and Poor's Register, the Canadian Directory of Associations in Canada, the American Encyclopedia of Associations, the membership directory of the Coal Association of Canada, the Directory of Principal International Businesses, the Canadian Trade Index, press articles, and suggestions from other companies.

Twenty-one of the fifty-eight Canadian companies contacted responded to the questionnaire, giving a response rate of 36%. Two of these firms declined to answer the questionnaire because they are not directly involved in fossil fuel production or utilization. Subsequent to the formal survey, an additional company was contacted for information related to this project. Thus the effective sample base is twenty companies, all but one of which are operating fossil fuel producers or transporters. Direct interviews to follow-up the questionnaire were conducted with four company executives. Two of these interviews were conducted in lieu of completing the questionnaire.

Eight of the fifteen associations and government-supported organizations contacted responded to the survey, resulting in a response rate of 53%. The respondents included six Canadian groups and the two foreign groups. One of the foreign groups could not supply any direct information. The effective size of this sample group was seven.

A list of survey participants is presented in Appendix B of this report.

LIGHT, HEAVY AND SYNTHETIC CRUDE OILS

According to the National Energy Board, fossil fuels (natural gas, natural gas liquids, coal and oil) account for 73% of all end use fuel demand in Canada. Oil (light, heavy and synthetic crudes) constitutes the single largest market segment, accounting for about 36% of the total energy used in Canada in 1987 compared with 23% for natural gas, 22% for hydro and nuclear electricity, 13% for coal and 6% for renewable resources.

Fortunately, Canada has a very large oil resource base. Although use of the term resource denotes that these deposits have not been fully delineated in terms of size or quality, it is known that ninety percent of this resource is in the form of bitumen. Conventional (light and heavy) oil accounts for only ten percent of the total resource base; and yet, at year end 1984, proven conventional crude reserves (those deposits that have been fully characterised and will be produced by known methods) amounted to 741 million cubic metres (about 28 exajoules). These reserves account for 53% of all remaining reserves. Conventional deposits in frontier areas, synthetic crude and bitumen account for 37% of remaining reserves; condensates (C_5+) account for the other 10%.

A telephone survey of the Departments of Energy for each province provided the following population distribution estimate for stripper wells (< 10 bpd production):

Alberta	5,000
Saskatchewan	6,500
Manitoba	9,000
Ontario	600
British Columbia	--
TOTAL	21,100 stripper wells

Enhanced oil recovery (EOR) is used when the crude oil being produced can not easily be pumped to the surface. According to Alberta's Energy Resources Conservation Board, EOR techniques have increased the average recovery rate of conventional oil reserves from 20% to more than 28%. The EOR projects implemented in 1987 were generally smaller and less capital intensive than previous years. At the end of 1987, 739 EOR projects were operating in Alberta.

Supplies of bitumen and heavy oil will increase as plant expansions and new projects are completed. These streams must be blended with condensate diluent in order to flow

through existing pipelines. Condensate supply is expected to remain flat or drop. Therefore there may be a shortage of diluent by the early 1990's, resulting in a bottleneck to the pipeline transport of bitumen and heavy oil. Possible solutions include using refinery run diluent. This option would be expensive and would reduce effective refinery capacities.

Oil-in-water emulsion technologies offer another possible solution. BP has developed its **Transoil** technology which is now being tested in collaboration with Alberta Energy. Canadian Occidental is also conducting emulsion tests. Heating the bitumen to reduce its viscosity or installing new pumps throughout a particular pipeline system are two other alternatives. Slower transportation times may be required for some of these options.

There are two ways in which biotechnology may enhance oil-in-water emulsion technologies for pipeline transport applications. Firstly, biosurfactants may be used to stimulate the formation of the emulsion. Secondly, dead microbial cells have been suggested as demulsification agents.

Aside from a relatively small asphalt market in summer, unprocessed heavy oil has few uses and must be transformed into lighter products. While there is a demand for heavy oil and bitumen in export markets, the key to long-term development will be upgrading the resources into lighter products here in Canada.

> *Moving heavy oil to market is a major challenge. If we can't match supply and demand then Canadian companies will lose those market opportunities.*
> (Quote from direct interview).

Although there was some dissension on the topic of microbial corrosion within the survey responses, the majority of industry contacts feel that microbial corrosion is an important issue. Most firms are aware of the molecular probe technologies now being developed.

Offshore development presents a unique and significant microbial corrosion problem. Experience in other parts of the world has given strong indication that biofouling and the associated process of biocorrosion play a significant role in affecting the performance of offshore rigs. Probably the most important (and troublesome for offshore engineers) bacteria which influence the corrosion behaviour of iron and steel are the sulphate-reducing types. Bacterial corrosion may proceed very rapidly and is dangerous because damage appears suddenly in very localized areas. Current studies in the United States are employing techniques of genetic engineering to develop antifouling agents by developing inhibitors that function at the molecular level. This method of control has great potential. The method used to control marine fouling should be an independent system which does not cause accelerated corrosion and prevents or removes fouling effectively. It must be cost-effective, easy to install and maintain (106).

Residue utilization is an area of significant and growing interest within the industry. Although no specific biotechnological solutions to this problem have been identified as of yet, the opportunity to integrate new microbial techniques with more conventional technologies exists.

In their 1986 Canadian Energy Supply and Demand Study, the Board predicted a trend towards increased importation of foreign fossil fuels to Eastern Canada. They cited a trend towards more coal imports from the U.S. to Ontario. The NEB also expects crude oil imports to the East Coast, Quebec and Ontario to rise by the early 1990's. Recent announcements of federal financial support for the Hibernia, OSLO and Bi-Provincial Upgrader projects may alter these predictions.

Canada's oil industry is dominated by large multinational companies. Although out-dated, the following tables indicate most of the major players in the business. At the other end of the scale, Statistics Canada estimates that there are roughly 500 small operating oil and gas companies (total assets and revenue less than $10 million). The special technology transfer needs of this group of smaller companies must be carefully considered.

Figure 6

Rank by Net Income 87	86	Integrated Oils
1	1	Imperial Oil
2	3	Shell Canada
3	2	Texaco Canada
4	5	Husky Oil
5	4	Parkland Industries

Figure 7

Rank by Net Income 87	86	Oil and Gas Producers
1	4	Chevron Canada Resources
2	2	PanCanadian Petroleum
3	3	Gulf Canada
4	1	Amoco Canada Petroleum
5	5	Mobil Oil Canada
6	29	Polysar Energy & Chemical
7	7	Norcen Energy Resources
8	8	Alberta Energy
9	10	Cdn. Occidental Petroleum
10	9	ATCO
11	15	BP Canada
12	11	Unocal Canada
13	24	Bow Valley Industries
14	25	Asamera
15	14	North Canadian Oils
16	31	Encor Energy
17	12	Scurry-Rainbow Oil
18	17	Ranger Oil
19	13	Canada Northwest Energy
20	30	Canterra Energy
21	23	Saskoil

Source: June 1988 Canadian Business

OPPORTUNITIES FOR APPLICATION IN CANADIAN INDUSTRY

COAL

In dollar terms, coal has assumed an increasingly important role on Canada's energy export stage. Valued at $1.696 billion in 1987, Canadian coal exports represented 12.7% of Canada's total energy exports, up from just 3.4% in 1970. Measured in energy units, coal now accounts for more than 20% of Canadian energy exports, up from 5% in 1970. However, consecutive years of price decreases has taken its toll on the industry. Annual capital expenditures have fallen from over $1 billion in 1982 to $326 million in 1987. Canada's coal reserves are enormous -- 2 trillion tonne. Based on current mining technologies and prices, 6 billion tonne is economically recoverable. The vast majority of these reserves lie in Alberta (110).

Ontario accounts for virtually all Canadian coal imports. Steel and utility producers in this province import roughly 15 million tonne of coal from the United States, as compared to total domestic coal production of slightly more than 61 million tonne in 1987.

The National Energy Board is predicting slow but steady growth in both thermal and metallurgical coal markets to the end of the century.

The Coal Association of Canada, in its publication Coal in Canada, suggests the following as technical challenges facing the industry:

Coal preparation:

There is a need to make coal a cleaner and cheaper fuel for electric power production. One of the major problems facing coal processing plants is the treatment of coal fines to achieve a higher quality clean coal product along with a higher overall coal recovery. Agglomeration of lower grade thermal coals appears to have considerable potential to produce higher quality marketable products which can be transported more economically over long distances.

Coal combustion:

Alumina, from which metallic aluminum is extracted, is present in quite high concentrations in fly ash, and research is underway to find an economical method of extracting it and recovering the aluminum.

Coal - liquid mixtures:

Canadian Cement Lafarge's Richmond B.C. plant is the first to convert from natural gas to coal/water slurry combustion. CANMET funded and technically supported this project.

Flue gas desulphurization:

Ontario Hydro's FGD Program expects to have to spend $3 billion to equip three coal-fired stations with scrubbers to reduce its annual acid gas emissions from 490,000 tonne in 1981 to 215,000 tonne in 1994 in order to meet Ontario's new environmental regulations.

In addition to the above, a survey of coal company executives suggests that a reduction in concentrations of inert materials (moisture and ash), new spontaneous combustion prevention techniques, and methods to avoid rail car plugging would be very beneficial to the industry.

Based on the technology review undertaken for this report, it is clear that bioleaching, gas desulphurization, and biosurfactant mediated coal surface modification technologies all hold significant promise for the industry.

NATURAL GAS

Natural gas production rose by 8% to 77.5 million m^3 in 1987 to satisfy increased export demand. Domestic demand is approximately 46 million m^3. The National Energy Board estimates that Canada had 92.9 exajoules of established marketable natural gas at year end 1986. There is significant potential for large reserve additions from both conventional and frontier areas. In fact, a number of large finds were announced in 1987 and 1988. Producers are looking for new markets for their abundant supply. Bioconversion, desulphurization of natural gas and dew point control, reclamation growth enhancement (removal residual herbicides), purification of saline contaminated triethylene glycol, waste water treatment, pipeline leak detection, and pipeline friction reduction are some of the technologies that will be of interest to the industry. The Canadian Gas Research Institute (acting on behalf of its membership) would be a potential collaborative R&D partner.

PROPOSED RESEARCH AND DEVELOPMENT PROGRAM

INTRODUCTION

For the purposes of this report, there are five primary observations to be made based on the information presented thus far in this report:

1. Some applications of biotechnology offer the potential for significant economic benefits to the fossil fuel industries
2. Some applications of biotechnology offer the potential to significantly reduce the deleterious environmental impacts of fossil fuel usage
3. A tremendous effort, both in terms of intellect and dollars, is required to develop and apply these technologies within the fossil fuel industries.
4. Given the size of Canada's fossil fuel resources and our nation's dependence on energy, the continued international competitiveness of our industries is vital to the well-being of our nation
5. The Energy Research Laboratories have a mandate to encourage industry to apply technological innovations for the improvement of their industrial competitiveness and the protection of the environment.

From these observations, it is concluded that the Energy Research Laboratories should have a specific budgetary allocation of dollars and person years to support the research and development of biotechnology applications for the fossil fuel industries.

Such budgetary allocations should be assigned to augment the positive aspects of the existing R&D effort, and minimize the barriers to the ultimate success of these efforts. The two surveys undertaken as part of this study invited respondents from industry, academia and government to cite barriers that may impede the adoption of advanced microbial technologies within the fossil fuels industry. Many respondents from the three sectors cited a low level of information exchange between sectors and a lack of collaboration between these groups as being major barriers. Researchers also cited inconsistent funding levels, industry's resistance to high risk/long term research, and a lack of access to suitable field test sites as major problems. Whereas, industry respondents tended to identify the high cost of research in this field as a major deterrent. The proposed program must effectively deal with these perceived barriers.

Furthermore, the survey revealed that most companies would prefer to collaborate with other companies to develop a new product or process. The five acceptable methods of research and development collaboration, as indicated by a large majority of the respondents, are presented here in decreasing order of preference:

- industry consortium
- joint venture with potential supplier
- cost shared project with government laboratory
- sponsored academic research
- contracted academic research.

It is particularly interesting to note that only a few industrial respondents identified the sixth optional answer (contract R&D to government lab) as being a preferred method of collaboration.

In reaction to these findings, this report suggests that the following plan be used to stimulate the further development and application of biotechnology for the fossil fuels industries:

Objective	Strategy
- promote information exchange between sectors	- expand the activities of the BIOMINET Network
- provide consistent funding	- allocate ERL funds to specific program elements for a reasonable length of time
- encourage R&D activities within universities	- support basic research
- encourage industrial R&D	- support applied R&D and the formation of industrial R&D consortia.

Therefore, this report proposes that ERL establish a Five Year Fossil Fuels Biotechnology Program. It is recommended that the funding and activities of this Program be divided among three separate program elements:

- Basic Research
- Applied Research
- Program Infrastructure.

The following pages describe each proposed element. It is fully expected that, upon further discussions between ERL, industry and universities, the specific research projects ultimately undertaken will differ somewhat from what is recommended in this report. Novel research project ideas should be solicited. Moreover, some projects already identified in this report as suitable for incorporation within a particular program element (ex. Basic Research) may ultimately be funded through one of the other elements (Applied Research or Program Infrastructure).

PROPOSED RESEARCH AND DEVELOPMENT PROGRAM

BASIC RESEARCH ELEMENT

The Need

In general, coal, oil and gas companies recognize and appreciate the support that academic research and development provides to industry. Yet corporate funding of basic research is low. Possible reasons for this low level of research support are:

- a perception that the financial risk associated with such investments is unacceptably high
- a belief that such investments are not required in order to reap the benefits of technological advancement
- complacency regarding the optimization of processes and products.

The Approach

1. Establish a Fossil Fuels Branch of BIOMINET, the initial membership of which will include all researchers and companies listed in Appendices A and B of this report.

2. Establish BIOMINET as the technical advisory committee to NSERC for biotechnology research related to the production and utilization of fossil fuels.

3. Establish a Basic Biotechnology Research Fund, the full cost of which will be borne by the federal government. The Fund will be used to support selected projects. These projects would be chosen from proposals submitted from Canadian universities, and other laboratories, to ERL via BIOMINET. Each principal investigator would be informed that she/he is not required to follow the specific details of the research plan as proposed, particulary if promising leads develop that seem likely to be more productive than the project as originally proposed. However, the investigator would have to inform BIOMINET of any proposed changes that deviate significantly from that described in the original proposal. Technology contamination is not expected to create difficulties for corporate members of BIOMINET as the projects to be reviewed will be of a basic research nature. However, the onus would lie with a company to choose a non-research representative, if technology contamination is a likely concern. This centralized approach should enable an informed, rationale and cost effective approach to project funding.

Topics to be addressed include, but will not be limited to the following items. Note that the majority of these suggestions have been put forward by King (76):

- Investigations of the transport phenomenon of microorganisms and nutrient in reservoir formations

- Microbial screening

- establishment of analytical procedures for screening and monitoring microbial activity
- develop and maintain a substrate catalogue
- develop compatibility models for microorganisms in field environments
- establish a repository of screened microorganisms
- develop a microbiological field reference manual for industry

o Fundamental hydrocarbon data to provide a more complete understanding of the structure and biogeochemistry of bitumen and heavy oil

o Review of research on microbial methods of sulphur, nitrogen and metals removal from heavy oil/bitumen and possibly a preliminary investigation of the most promising approach

o Review of research on microbial methods of CO_2 removal from a gaseous stream and, possibly, a preliminary investigation of the most promising approach

o Bioconversion of natural gas or methanol

o Bioprocessing of waste waters

o Bioprocessing of oily sludge/residues/pitch

o Corrosion avoidance

o Lubricant product development

o Microbial prospecting for oil or gas

o Bioregeneration of spent catalyst

o Laboratory protocols identifying reasonable and reproducible starting points, determinant variables, and required outputs to be measured or determined.

APPLIED RESEARCH ELEMENT

The Need

Data from well-designed field tests is required to accurately assess the commercial viability of any bioprocess. Such data is conspicuously absent from the literature. This fund will be used to address the chemical and biochemical engineering aspects of applying microbial technologies to the production and utilization of fossil fuels.

For the most part, modern biochemical engineering is focused on low volume, high value products; a different approach will be required to optimize bioprocesses for the fossil fuel industries.
Data from major MEOR field test programs currently underway in other countries will not be directly transferable to Canadian reservoirs. Moreover, such data is usually most available to parties who are undertaking similar or associated work and who can, or will subsequently, supply data of their own to the international body of knowledge. Two examples of major MEOR initiatives are:

- The U.S. Department of Energy (DOE), the National Institute for Petroleum and Energy Research (NIPER), Microbial Systems Corp. and INJECTECH Inc. are collaborating in a comprehensive field test at Nowata, Oklahoma which began in October of 1986. The site consists of four adjacent inverted five-spot patterns drilled on a five acre plot in the Mink Unit of Delaware-Childers field. A statistically significant increase in oil production was evident six months after treatment began (82).

- A $1.2 million, 21 month trial has recently been announced in Australia. Five organizations, including the Department of Primary Industries and Energy (through its National Energy Research, Development and Demonstration Program) and a number of private companies, have established a joint venture R&D agreement to undertake this work. The project is being led by Dr. Alan Sheehy, of the Canberra College of Advanced Education (108).

- The DOE recently announced another major MEOR project to field test a process developed at the University of Oklahoma. This in situ selective plugging process is aimed at improving reservoir sweep efficiencies. The three and a half year budget for this project is $780,000. The DOE is providing $630,000; the remainder of the cost is being shared by the University and a private petroleum company.

The Approach

1. A **Proof of Concept Fund** should be established to support the salary, capital and operating budget for one person for one year. This person (employee or guest) will work in an industrial setting to demonstrate a proposed technology on a small scale. Additional support will be made available by providing this individual with access to CANMET facilities and expertise.

2. A special, one time only, capital budget item will be established to finance the construction of a **physical reservoir simulator facility** to be used for MEOR laboratory testing. This facility should be located in Calgary, and should build upon existing expertise and equipment. This proposed funding should be used to fill in the

gaps in terms of equipment available for MEOR system development, including system scale-up. The ability to simulate actual in situ conditions should be emphasized in the deign of the new equipment.

3. An **Applied Research Fund** should be established to deliver financial support to selected projects on a cost shared basis with industry. This report also suggests the establishment of an industrial R&D consortium (see following section: Management). It is expected that ERL's Applied Biotechnology Research Fund will be used to match investments made by this consortium or by individual companies.

As these technologies are to be developed for industrial application, the specific projects will be best chosen based on actual requests from industry for government funding. However, based on confidential information obtained from the survey participants for this report, the following proposed activities and possibly interested parties are presented for consideration.

o MEOR Field Test

Nova Husky Research, Canadian Hunter Exploration, Esso Resources, Shell Canada, AOSTRA, ARC, SRC. Strong consideration should be given to demonstrating well bore cleaning of stripper wells as a first priority. The methodology of target definition should be demonstrated. MEOR field trial monitoring protocols should be developed. ERL should investigate whether high technology sensing equipment, such as that being used for the Lithoprobe study, might be usefully applied to monitoring an MEOR field test.

o Soil Reclamation

The microbiological characterization of a specific hydrocarbon processing plant site could be a starting point for a collaborative project aimed at identifying and understanding microbiological soil reclamation principles and best available technologies, and the important parameters to be considered when evaluating this approach in comparison with non-biological methods of soil reclamation.

Nova Husky Research, Canadian Gas Research Institute, Esso Resources, Shell Canada, AOSTRA, ARC, SRC.

o Screening and Production of Biosurfactants: (for applications in)

- coal surface modification to enhance solubilization, the physical separation of impurities, and reclamation of waste coal fines;
- bitumen and heavy oil extraction (in situ and above ground); and,

- emulsification of heavy oils and bitumen for facilitated recovery, collection and pipelining.

Domtar, Canadian Hunter Exploration, Cape Breton Development, Esso Resources, Manalta Coal, Obed Mountain Coal, Shell, Syncrude, AOSTRA, ARC, SRC.

o Microbial Desulphurization of Sour Gases:

Canadian Gas Research Institute, Canadian Hunter Exploration, Cape Breton Development, Esso Resources, Shell Canada, Syncrude, Nova Husky Research, AOSTRA, ARC, SRC.

PROGRAM INFRASTRUCTURE

While this report does not suggest that ERL undertake any direct research and development activities within its in-house laboratories, there are a number of equally important functions for which ERL is very suitably prepared:

Soundingboard for industrial and academic innovators

- ERL should have staff available who can provide informed opinion and objective critique to research and development projects; active participation in projects, a well as contract administration, would be very beneficial.

Dissemination of technical information

- ERL should operate at a national level to provide advice and information to companies through direct communications, publications, and sponsored symposia; and should promote success stories. This responsibility could be fulfilled via ERL's active support and involvement in BIOMINET.

Development and dissemination of market information

- ERL should commission cost estimate studies and techno-economic evaluations; promote Canadian technologies and products; and report on industrial technology requirements, and new technology and new product developments. This role could also be achieved through BIOMINET.

Information collection

- ERL should utilize its extensive network of contacts to gather information from within Canada and from international sources.

Coordination of activities

- ERL should coordinate biotechnology activities with other related programs and offices, such as the:

  - o Natural Science and Engineering Research Council's (NSERC) Strategic Grants and University/Industry Programs
  - o National Research Council's (NRC) Biotechnology Program (including, but not to be limited to, the microbiological, genetic engineering, and analytical capabilities and knowledge both at the Biotechnology Research Institute [BRI] in Montreal and at the Division of Biological Sciences [DBS] in Ottawa). Soil reclamation activities at BRI, and waste water treatment studies at both BRI and DBS may be particularly relevant.
  - o National Research Council's recently launched Resource Processing Program which is aimed at assisting natural resource based industries to applied new technological advancements to improve their international competitiveness
  - o Industry, Science and Technology Canada's (ISTC) Strategic Technology Alliance Program
  - o Energy, Mines and Resources Canada's (EMR) Bioenergy Program
  - o Institute for Chemical Science and Technology (ICST)
  - o Petroleum Association for Conservation of the Canadian Environment (PACE), and
  - o other organizations not yet identified.

MANAGEMENT

The primary objective of the management structure should be to facilitate maximum collaboration between technology developers and potential technology users, with the emphasis on perceived need within industry as opposed to, but not totally in place of,

technological opportunity. As such industry must have a large say in the final design of the program management structure, activities and budget. The proposals made herein are presented as a starting point for discussions between industry, universities and ERL/CANMET. This report suggests that BIOMINET is an obvious vehicle for such discussions.

It is therefore suggested that a FOSSIL FUELS BRANCH OF BIOMINET be established. Membership in this branch will be open to all oil, coal and gas operating, R&D, and supply and service companies. All interested university and government researchers will also be invited to join. The list of survey participants presented in Appendices A and B are a possible starting point for the initial membership list for this new branch of BIOMINET. There should be no membership fee to join this branch.
The objectives of the FOSSIL FUELS BRANCH will be to:

- o support R&D to fill gaps in knowledge and expand in directions of potential interest to industry
- o assist companies to collect and evaluate the body of information in this area, and to stay informed of all new developments that may be pertinent to their operations
- o promote the establishment of industrial consortia to investigate specific applications
- o identify projects that merit field testing or scale-up to pilot or demonstration stage, encourage private sector participation, and support the cost of such activities
- o design R&D projects to best fit existing R&D assistance programs.

One of the two person years proposed to be supplied by ERL to the biotechnology program should be responsible for the secretaryship of this new branch of BIOMINET, and should support the activities of the existing Chairman and Secretary of BIOMINET.

It is proposed that the second ERL person year be devoted to the establishment of a NON-PROFIT CORPORATION FOR COLLABORATIVE R&D.

This corporation would invite membership from Canadian companies and crown corporations having an active research and development operation that could benefit from the activities to be performed through the corporation.

The Corporation could be designed in a similar fashion to the PRECARN Associates Inc. model (107). The following operating guidelines are proposed:

- an annual membership fee levied to all members would be used to support basic biotechnology research for the production and utilization of fossil fuels
- the Fossil Fuels Branch of BIOMINET would act as the Technical Advisory Committee to the Corporation
- the Corporation would maintain ownership of resultant technology and would grant licences to members (conditions of which may vary depending upon the degree of support and funding supplied by each member to the particular research agreement)
- all members will have the right to use research results for R&D uses only
- Corporation members would have the opportunity to undertake more ambitious projects through research agreements
- willing members would share the expenses of a particular research agreement and maintain confidentiality within the membership
- supporting members would have no-charge access on a confidential and reasonable time basis to researchers preforming work under a research agreement
- the Corporation would generally support the publication of funded research; however, a delay of publication may be negotiated with supported researchers (up to two years), depending upon the nature of the work and the degree of support received from the Corporation
- the Corporation would apply for a special dispensation from Treasury Board for the transfer of ownership of intellectual property funded 100% by the Corporation to said Corporation from the Crown, with the researchers retaining residual rights for in-house research purposes
- the Corporation may seek royalty bearing non-exclusive licences for the results of research which was conducted in a cost shared manner with the Crown.

The individuals involved in this program will be key to the program's success. The ERL personnel chosen to work in the program must be very knowledgeable about the industries concerned and have, or quickly develop, an understanding of biotechnology.

BUDGET

Proposed Budget Items:

1.0 **Basic Research Element**

1.1 Core funding of $100,000 for each of Years 1 through 5. This funding will be granted on a single year basis only. Researchers would submit their applications for any amount up to the $100,000 total funding available. After the annual application deadline, BIOMINET would screen the applications and forward those that pass the peer review to ERL for consideration. ERL would have the decision as to how to disburse the $100,000 among the applications; no doubt some applications would have to be rejected. Researchers could submit applications for second or third year funding support for an existing project.

2.0 **Applied Research Element**

2.1 *Proof of Concept* Fund: $75,000 per year for five years.
Note that to be eligible for funding the work must be performed within an established industrial R&D or production facility. The funds are intended to support one project per year. Projects and individuals who receive funding for one year will not be eligible for future funding under this program element. Applications for this Fund would be submitted directly to ERL, who would hold all submissions in confidence.

2.2 Special one-time capital allowance of up to $100,000 for the design and construction of physical MEOR simulation equipment to be used to expand upon an existing facility's simulation and scale up capabilities. This facility must be available, on a charged fee basis, to the industry at large.

2.3 Applied Research Fund: $ --- for Year 1
300,000 for Year 2
300,000 for Year 3
300,000 for each of Years 4 and 5.

As this funding is to be applied only to cost shared projects with industry, it is suggested that no funds be dispersed in the first year of the five year program. During the first year efforts should be devoted to establishing the basic research program, the other aspects of the applied research element (namely the *proof of concept* fund and physical simulator facility), the program infrastructure, and management system (including the proposed industrial R&D consortium).

The budget should be set at the end of the first year for the remaining four years of the program; a single year carryover of 75% of the unspent annual budget should be allowed. Individual funded projects should be allowed to carry over lapsed funds from one year to the subsequent year. It is understood that industrial investment will be also be leveraged through other appropriate government programs (see Coordination Item under Proposed Activities: Infrastructure support).

3.0 Program Infrastructure

3.1 It is proposed that ERL provide two person years to this Program for the five year period, at a combined estimated cost of $150,000 per year.

TOTAL PROPOSED BUDGET: $2.925 million over five years.

KEY PERFORMANCE INDICATORS

The following key performance indicators should be used to monitor and report on the progress made through this Program, on an annual basis:

- number of R&D personnel employed in the field of biotechnology for the production and utilization of fossil fuels within the Canadian public and private sectors
- frequency of use of established methods in data generation
- number of market studies and techno-economic evaluations performed for this field of application
- number of microbial ecology and environmental impact assessments developed in this field of application
- number of field trials conducted
- number of successful field trials
- level, and changes in the level, of financial investment by industry in this field of application.

REFERENCES

1. Sublette, K.L. Microbiological Desulfurization of Gases. European Patent Application No. 0244659. Filed April 8, 1987. Assigned to Combustion Engineering, Inc.

2. Horikoshi, K. and Shibanai, I. Process For The Oil Extraction From Oil Sand By Using Cyclodextrin. Canadian Patent 1,168,612. Issued June 5, 1984. Granted to Kenyusho, R. and Shibanai, I.

3. Thompson, B.G. and Jack, T.R. Method of Enhancing Oil Recovery by Use of Exopolymer-Producing Microorganisms. Canadian Patent 1,196,303. Issued December 11, 1985. Granted to Nova/Husky Research Corp. Ltd.

4. Stevens, S.E. and Burgess, W.D. Biological Desulfurization of Coal. Canadian Patent 1,210,349. Issued June 26, 1986. Granted to The Standard Oil Company.

5. Worne, H.E. and Rabinovitch, I. Process of Microbial Extraction of Hydrocarbons From Oil Sands. Canadian Patent 1,154,701. Issued November 4, 1983.

6. McCready, R.G.L., Coleman, R.D., Capes, C.E., Kempton, A.G. and Moneib, N.A.M. Bioadsorption Alteration of Iron Sulfide Surfaces. Canadian Patent 1,145,144. Issued April 26, 1983. Granted to Canadian Patents and Development Limited.

7. Zajic, J.E. and Knetting, E. Emulsifying Agents of Microbiological Origin. U.S. Patent 3,997,398. Issued December 14, 1976. Granted to Canadian Patents and Development Limited.

8. Zajic, J.E. and Gerson, D.F. Hydrocarbon Extraction Agents and Microbiological Processes For Their Production. Canadian Patent 1,114,759. Issued December 22, 1981. Granted to Canadian Patents and Development Limited.

10. Myerson, A.S. and Ernst, W.R. Removal of Inorganic Contaminants From Catalysts. U.S. Patent 4,559,313. Issued December 17, 1985. Assigned to Georgia Tech Research Institute.

11. Krishna, C.R., Francis, A.J., Dodge, C.J. and Sproull, R.D. Enhancement of Coal Quality By Microbial Demetalization and Desulfurization. Biological Treatment of Coal Workshop. D.O.E. Contract No. DE-ACOZ-76CH00016.

12. Vaseen, V.A. and Attia, Y.A. Commercial Microbial Desulphurization of Coal. Processing and Utilization of High Sulphur Coals, 1985. p. 699-715.

13. Hitzman, D.O. Petroleum Microbiology and the History of Its Role in Enhanced Oil Recovery. International Conference on Microbial Enhancement of Oil Recovery. February, 1983. p. 162-218.

14. Springham, D.G. et al. Some Constraints on the Use of Bacteria in Enhanced Oil Recovery. International Conference on Microbial Enhancement of Oil Recovery. February, 1983. p. 158-161.

15. Bryant, R.S. Transformation of Hydrocarbon by Microorganisms. National Institute for Petroleum and Energy Research. Report No. NIPER - 213. November, 1986. p. 22.

16. Bryant, R.S. Environmental Effects of Microbial Enhanced Oil Recovery Processes. National Institute for Petroleum and Energy Research. Report No. NIPER - 171. July, 1986. p. 6.

17. Lazar, I., Donaldson, E.C. and Clark, J.B. Microbial Enhancement of Oil Recovery in Romania. International Conference on Microbial Enhancement of Oil Recovery. February, 1983. p. 140-148.

18. Lazar, I. Microbiological Methods in Secondary Oil Recovery. Enhanced Oil Recovery Europe Symposium. 1979. p. 279-287.

19. Zhang, Z. and Qin, T. Survey of Research on the Microbial Enhancement of Oil Recovery. International Conference on Microbial Enhancement of Oil Recovery. February, 1983. p. 135-139.

20. Marquis, R.E. Barobiology of Deep Oil Formations. International Conference on Microbial Enhancement of Oil Recovery. February, 1983. p. 124-128.

21. Westlake, D.W.S. Microbial Activities and Changes in the Chemical Physical Properties of Oil. International Conference on Microbial Enhancement of Oil Recovery. February, 1983.

22. Crawford, P.B. Possible Reservoir Damage From Microbial Enhanced Oil Recovery. International Conference on Microbial Enhancement of Oil Recovery. February, 1983.

23. Yarbough, H.F. and Coty, V.F. Microbially Enhanced Oil Recovery From the Upper Cretaceous Nacatock Formation, Union County, Arkansas. International Conference on Microbial Enhancement of Oil Recovery. February, 1983.

24. Carrol, H.C. and Linville, B. EOR: What Those New Reserves Will Cost. Petroleum Engineer International. November, 1986.

25. Hitzman, D.O., King, J.W. and Stevens, D.A. Summary of MEOR Field Tests With a Look to the Future. Proceedings of the First International MEOR (Microbial Enhanced Oil Recovery) Workshop. January, 1987. p. 257-268.

REFERENCES

26. Singh, S., Nguyen,D., Grieco, J., de Rocco, M., Costerton, J.W., Cusack, F., and Lappin-Scott, H. Reservoir Plugging/Blocking Using Ultramicrobacteria: Three-Dimensional Physical Simulator Results. Fourth UNITAR/UNDP Conference on Heavy Crude and Tar Sands. Paper No. 218. 1988.

27. Alpha Environmental Testing MEOR at Five Leases. Enhanced Recovery Week. September 21, 1987. p. 1-3.

28. Jack, T.R. Microbially Enhanced Oil Recovery. Biorecovery. 1988. Vol.1, pp. 59-73.

29. Grist, D.M. Microbial Enhancement of Oil Recovery - An Operator's View. International Conference on the Commercial Applications and Implications of Biotechnology. London, U.K. 1983. p. 463-474.

30. Finnerty, W.R., Singer, M.E. and Meyer, R.F. Microbial Processors and the Recovery of Heavy Petroleum. 2nd. International Conference on Future of Heavy Crude and Tar Sands. Caracas, Venezuela. February 7, 1982.

31. Finnerty, W.R. and Meyer, R.F. Role of Microbiology in Enhanced Oil Recovery. Long-Term Energy Resources. Volume I.

32. C-E (Combustion Engineering). Environmental Journal, Summer 1988, Vol.2, No.3.

33. Jack, T.R. Biotechnology in the Production of Heavy Oil and Oil Sands. Biotech '83.

34. Zajic, J.E. Considerations in the Injection Technology For Microbial Enhanced Oil Recovery. 20th Intersociety Energy Conversion Engineering Conference. August 18, 1985. p. 673-680.

35. Pallister, J.M. and Van Ruskenveld, Y. Technology Development in the Oil and Gas Industry. For MOSST. May, 1986.

36. Sublette, K.L. and Sylvester, N.D. Oxidation of Hydrogen Sulfide by Mixed Cultures of Thiobacillus Denitrificans and Heterotrophs. Biotechnology and Bioengineering, Vol. XXIX, pp.759-761, 1987.

37. Savery, W.T., De Four, M.A. and Janshekar, H. Potential Uses of Microbes For Continuous Near-Wellbore Treatment During Heavy Oil Production. Third International Conference on Heavy Crude and Tar Sands. Long Beach, California. USA. July 22-31, 1985.

38. Olsen, D.K. and Janshekar, H. Biosurfactant Production and Laboratory Application Tests For Heavy Crude Oil. Third International Conference on Heavy Crude and Tar Sands. Long Beach, California. USA. July 22-31, 1985.

39. Bryant, R.S. and Douglas, J. Evaluations of Microbial Systems in Porous Media For Enhanced Oil Recovery. SPE International Symposium on Oilfield Chemistry. San Antonio, Texas. USA. February 4-6, 1987.

40. Haggin, J. Newly Developed Bacterial Strain Removes Organic Sulfur From Coal. Chemical and Engineering News. August 29, 1988. p. 36-37.

41. Beyer, M. Microbial Removal of Pyrite From Coal Using A Percolation Bioreactor. Biotechnology Letters. Volume 9, No. 1, December 16, 1987. p. 19-24.

42. Beyer, M., Ebner, H.G. and Klein, J. Influence of Pulp Density and Bioreactor Design on Microbial Desulphurization of Coal. Applied Microbiology and Biotechnology. July, 1986. p. 342-346.

43. Fannin, K.F., McKinley, V.L. and Maka, A. Microbial Removal of Organic Sulfur From Coal. Fourth Quarterly Report, July - September, 1986. Institute of Gas Technology Project No. 61078. For U.S. Department of Energy. DOE Contract No. DE-AC22-85PC81201.

44. Kargi, F. Microbial Methods For Desulphurization of Coal. Trends Biotechnology. Volume 4:11. November, 1986. p. 293-297.

45. Bos, P., Huber, T.F., Kos, C.H., Ras, C., Keunen, J.G., Lawrence, R.W.,Branion, R.M.R. and Ebner, H.G. Dutch Feasibility Study on Microbial Coal Desulfurization. Fundamental and Applied Biohydrometallurgy. 1986. p.129-150.

46. Huber, T.F., Ras, C. and Kossen, N.W.F. Design and Scale-up of a Reactor For the Microbial Desulfurization of Coal: A Kinetic Model For Bacterial Growth and Pyrite Oxidation. Third European Congress on Biotechnology . Vol. 3. 1984. p. 151-159.

47. FY88 Annual Research Plan. National Institute For Petroleum and Energy Research. Report No. NIPER - 260. October, 1987.

48. CANMET Business Plan, 1988-1991. Canada Centre for Mineral and Energy Technology. Energy, Mines and Resources Canada. November, 1987.

49. ERL, Business and Strategic Plan, 1987-1990. Energy Research Laboratories. Energy, Mines and Resources Canada. March, 1987.

REFERENCES

50. Gutnick, D. Biosurfactants and the Oil Industry. Proceedings of Biotech '84, USA. Volume 2, p. 645-653.

51. Bryant, R.S. and Douglas, J. Significance of the Survival and Performance of Bacillus Species in Porous Media for Enhanced Oil Recovery: Topical Report. Report No. NIPER - 179. March, 1987. p. 24.

52. Bryant, R.S. Use of Mixed Cultures to Determine Potential Environmental Hazards of Microbialiy Enhanced Oil Recovery Research. Report No. NIPER - 91. August 1985.

53. Bryant, R.S. and Douglas, J. Survival of MEOR Systems in Porous Media. Report No. NIPER - 105. March, 1988.

54. Jack, T.R., Yen, T.F., Kawahara, F.K. and Hertzberg, R. Enhanced Oil Recovery by Microbial Action. Chemical and Geochemical Aspects of Fossils Energy Extraction. 1983. p. 13-22.

55. Smith, R.J and Collins, A.G. State of the Art Microbial Enhanced Oil Recovery: A Review of the Literature. Report No. NIPER - 12. October, 1984.

56. Bryant, R.S. and Douglas, J. State-of-the-Art Review: Microbial Field Technology. Report No. NIPER - 138. June, 1986. 11 p.

57. King, J.W. MEOR (Microbial Enhanced Oil Recovery) Technical Status and Assessment of Needs. 1986. DOE Report No. DOE/BC/10852-2. March, 1987. p. 49.

58. Finnerty, W.R. Biosynthesis of a Microbial Biosurfactant Progress Report. DOE Report No. DOE/ER/10683-5. April 1, 1984. 24 p.

59. Sublette, K.L. Aerobic Oxidation of Hydrogen Sulfide by Thiobacillus Denitrificans. Biotechnology and Bioengineering, Vol. XXIX, pp. 690-695. 1987.

60. Sublette, K.L, and Cusack, J. Removal of Hydrogen Sulfide From Gases with Thiobacillus Denitrificans. 8th International Biotechnology Symposium, Paris, France. July 17-22, 1988., Poster Presentation #B48.

61. Pyne, J.W. and Wilson, B.W. Biological Coal Beneficiation: Literature Review: Final Report. EPRI Report No. EPRI-AP-4834. November, 1986. 38 p.

62. Zurer, P.S. Study Traces Most SO_2 Emissions to Burning of Moderate-Sulphur Coal. Chemical and Engineering News. June 27,1988. p. 40-41.

63. Rai, C., Markuszewski, R. and Blaustein, B.D. Microbial Desulphurization of Bituminous Coals. Fossil Fuels Utilization. Environmental Concerns. 1986. p. 86-97.

64. Henderson, C.B., Isbister, J.D., Kobylinski, E.A. and Sakkestad, B.A. Microbial Desulphurization of Coal. Proceeding of the Tenth International Conference on Slurry Technology. 1985. p. 209-215.

65. Ward, B., Egneus, H. and Ellgard. A. Apparent Bioliquefaction of Lignite by Fungi and Their Growth on Lignite Components. Bioenergy 84. Volume 3. Biomass Conversion. 1985. p. 284-288.

66. Olson, G.T. and Brinckman, F.E. Bioprocessing of Coal. Fuel. Volume 65. No.12 December, 1986. p. 1638-1646.

67. Couch, G.R. Biotechnology and Coal. International Energy Agency Coal Research Report No. ICTIS/TR-38. March, 1987. 56 p.

68. Microbial Surfactant Recovers Waste Oil. Chemical and Engineering News. February 22, 1988. p. 18

69. Bacteria Show Promise in Soil Cleanup. Chemical Week. May 4, 1988. p. 43.

70. How the SITE Program Works. Chemical Week. February 24, 1988. p. 43.

71. A New Entry in Hazardous Waste Site Cleanup. Chemical Week. February 24, 1988. p. 30.

72. McCready, R.G.L. and Zentilli. M. Feasibility Study on the Reclamation of Coal Waste Dump by Bacterial Leaching. CIM Bulletin. Volume 78:876. April, 1985. p. 67-68.

73. Moses, V. and Brown, M.J. MEOR Systems: Problems of Design and Scale-Up. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug. 12-13, 1987. pp 1.

74. Clausen, E.C., Gaddy, J.L., Ghate, M.R., Markel, K.E. Jr., Jarr, L.A. and Bossart, S.J. Advanced Studies of the Biological Conversion of Synthesis Gas to Methane. Proceedings of the Seventh Annual Gasification and Gas Stream Cleanup Systems Contractors Review Meeting: Volume 2. August, 1987. p. 526-529.

75. Cooper, D.G., Pillon, D.W., Mulligan, C.N. and Sheppard, J.D. Biological Additives for Improved Mechanical Dewatering of Fuel-Grade Peat. Fuel. Volume 65:2 February, 1986. p. 255-259.

REFERENCES

76. King, J.W. MEOR - A Solution to Our Current Domestic Oil Supply. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. II.

77. Douglas J., Bryant, R.S., and Bertus, K. Environmental Aspects of Microbial Enhanced Oil Recovery. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. III.

78. Horacek, G. Biocorrosion in the Oilfield. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp.IV.

79. Watson, J.S. and Scott, C.D. Potential Roles for Bioprocessing in Enhanced Oil Recovery. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. V.

80. Hitzman, D.D. Review of Microbial Enhanced Oil Recovery Field Tests. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. VI.

81. Jack, T.R. and Stehmeier. Selective Plugging in Watered Out Oil Reservoirs. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. VII.

82. Dennis, M. Microbial Enhanced Waterflood Project. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. IX.

83. Bryant, R.S., Burchfield, T.E., Doulgas, J. and Bertus, K. Laboratory Optimization of Microbial Field Projects. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. X.

84. Cruze, J.A. and Hitzman, D.O. Microbial Field Sampling Techniques for MEOR Processes. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. XI.

85. Oppenheimer, D.H. and Heibert, F.K. Microbial Enhanced Oil Production Field Tests in Texas. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. XII.

86. Raiders, R.A., Knapp, R.M., McInerney, M.J. and Menzie, D.E. Microbial Selective Plugging and Enhanced Oil Recovery. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. XVI.

87. Burchfield, T.E. and Carrol, Jr., M.B. Economics of MEOR Processes. Proceedings of the Symposium on Applications of Microorganisms to Petroleum Technology. Bartlesville, Oklahoma. Aug.12-13, 1987. pp. XIX.

88. Akin, C. Gas, Oil, and Coal Biotechnology - An Emerging Industry. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

89. Kelly, R.L., Conrad, J.R., Hoefer, D.E., Srivastava, V.J. and Akin, C. Physiologic and Engineering Parameters in Potential Commercialization of Methanotrophs. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

90. Yunker, S.B. EPRI (Electric Power Research Institute) Focus on Application of Biotechnology to Utility Problems. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

91. Kilbane, J.J. Biodesulphurization of Coal. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

92. Ward, B., Quigley, D.R. and Dugan P.R. Relationship Between Natural Weathering and Lignite Biosolubility or Alkali Solubility. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

93. Maka, A. and Akin, C. Microbial Solubilization and Gasification of Lignite. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

94. Barik, S., Anspach, G., Wyza, R., Hawley, B. and Isbister, J. Biological Conversions of Low-Rank Coals. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

95. Sriharan, S., Dahlberg, M.D., Speers Jr., V.A. and Bagga, D. Bioconversion of Coal: Partial Purification of Ligninase From *Phanerochaete chrysosporium*. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

96. Elmore, B.B., Vega, J.L., Ackerson, M.D., Clausen, E.C. and Gaddy, J.L. Bioconversion of Synthesis Gas into Ethanol or Methane. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

REFERENCES

97. Fox, B.G., Froland, W.A. and Lipscomb, J.D. Biochemistry of the Bacterial Oxidation of Methane. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

98. Hanson, R.S., Tsuji, K., Bastien, C., Tsien, H.C., Bratina, B., Brusseau, G. and Machlin, S. Genetic and Biochemical Studies of Methylotrophic Bacteria. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

99. Vega, J.L., Antorrena, G.M., Clausen, E.C. and Gaddy, J.L. Bioreactor Design for Gaseous Substrate Fermentations. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

100. Cusak, F., MacLeod, F.A., Costerton, J.W. and Lappin-Scott, H.M. Formation and Utilization of Ultramicrobacteria to Enhance Oil Recovery by Selective Plugging. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

101. Misra, A.K., Nripendra, K.B. and Johnson, J. Some Aspects of Microbial Enhancement of Oil Recovery. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

102. Shively, J.M., Fitzgerald, E.G., English, R.S., Williams, C.A., Dang, C., Stoner, M.T. and Blake, R. Genes for the Large Subunit (+bcL) of Ribulose Bisphosphate Carboxylase/Oxygenase (RuBisCo) in the Thiobacilli. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

103. Srivastava, V.J., Kilbane, J.J., Kelley, R.L., Akin, C., Hayes, T.D. and Linz, D.G. Biodegradation of Old Town Gas Site Wastes. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

104. Sherman, D.F., Stroo, H. and Bratina, J. Degradation of PAHs in Soil Utilizing Enhanced Bioremediation. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

105. Blackburn, J.W. Microbial Systems Analysis For Increased Predictive Reliability in Polyaromatic Hydrocarbon Bioremediations. IGT Symposium in Gas, Oil, and Coal Biotechnology. Chicago, Illinois. Dec. 5-7, 1988.

106. Frantsi, C., Coatas-Markle, L., Whalen, K.A., Bacon, G.B. and Picken, G.B. Biofouling Considerations in the Development of Atlantic Canada's Offshore Petroleum Industry. Energy Mines and Resources Canada. DSS File No. 155Q 23440-4-9241. March, 1985.

107. Precarn Associates Inc. The Business Plan, May 1, 1987 and Membership Agreement, Sept. 9, 1988.

108. Use of Bacteria Studied for EOR Programs. Oilweek. March 14, 1988. P.5.

109. Harris, P. (ed.). Energy in Canada, 1988-1989. Southam Communications Limited. ISBN 0828-5179.

110. National Energy Board. Canadian Energy. Supply and Demand 1985-2005. Minister of Supply and Services Canada 1986. Cat. No. NE23-15/1986-1E.

111. Karaskiewicz, J. Application of microbiological methods for prospecting crude oil and natural gas deposits. Pr. Inst. Naft. 1970. P.3-62.

112. Brown, M.J. Novel Biosurfactants for EOR. Proc. 3rd European Meeting of Oil Recovery. 8504250, P.241-248. 1985.

113. McInerney , M.J. Physiological Types of Microorganisms Useful for Enhanced Oil Recovery. Proc. Inter. Conf. on Microbial Enhancement of Oil Recovery. Aston, Oklahoma. 8205140. P.38-42. 1983.

APPENDIX A

LIST OF PHASE I SURVEY PARTICIPANTS

(State-of-the-Art Technology Assessment)

CANADA

Dr. F.M. Kimmerle
Chief Anal. Chemist
Arvida Research and Development Centre
Alcan Aluminum Ltd
P.O. Box 1250
Jouquiete, Quebec, 67S 4K8
Telephone: 418-699-2851
Telefax: 418-699-3996

Mr. M.J. Desrochers
Group Leader/Biotechnology
Domtar Inc.
C.P.300
Senneville, Quebec, H9X 3L7
Telephone: 514-457-6810

Mr. R.D. Hayes
Chief, Bioenergy Research and Development
Bioenergy Division; Renewable Energy Branch;
Energy, Mines and Resources
460 O'Connor Street
Ottawa, Ontario, K1A 0E4
Telephone: 613-996-6227

Dr. R.J. Neufeld and Dr. D.G. Cooper
Associate Professors
Department of Chemical Engineering
McGill University
3480 University Street
Montreal, Quebec, H3A 2A7
Telephone: 514-398-4275
Telefax: 514-398-6678

Dr. C. Greer
Research Officer
Biotechnology Research Institute
National Research Council
6100 Royalmount Avenue
Montreal, Quebec, H4P 2R2
Telephone: 514-496-6182
Telefax: 514-496-6232

Dr. G.T. Cooper
Group Leader - IRAP, BIOTECH
National Research Council
Building M-55, Montreal Road
Ottawa, Ontario, K1A 0G6
Telephone: 613-993-5539
Telefax: 613-952-1079

Dr. T.R. Jack
Manager - Applied Sciences
Nova Husky Research Corporation
2928 16th Street N.E.
Calgary, Alberta, T2E 7K7
Telephone: 403-250-4751
Telefax: 403-291-3208

Dr. D. Westlake
Professor
Department of Microbiology
University of Alberta
Edmonton, Alberta, T6G 2E2

Dr. J.W. Costerton
AOSTRA Professor of Microbiology
University of Calgary
Calgary, Alberta, T2N 1N4
Telephone: 403-220-7301
Telefax: 403-289-9311

Dr. A.W. Neumann
Professor
Department of Mechanical Engineering
University of Toronto
Toronto, Ontario, M5S 1A4
Telephone: 416-978-3601

UNITED STATES

Dr. D.M. Updegraff
Research Professor (Retired)
Department of Chemistry/Geochemistry
Colorado School of Mines
Golden, Colorado 80401
Telephone: 303-271-3580

Mr. J. Cusack
Director of Technology Marketing and Development
Combustion Engineering
T. Becker Fram Road
Roseland, New Jersey 07068
Telephone: 201-992-2323
Telefax: 201-992-2392

Dr. J.W. King
Director, Energy Division
Hardin-Simmons University
Fairleigh Dickinson Research Centre
1249 Ambler Avenue
Box 140 HSU Station
Abilene, Texas 79698
Telephone: 915-677-1386 Ext. 9
Telefax: 915-677-8447

Dr. G. Andrews
Senior Engineering Specialist
Biotechnology Unit
Idaho National Engineering Laboratory
P.O. Box 1625
Idaho Falls, Idaho 83415
Telephone: 208-326-0174

Dr. R. Smith Bryant
National Institute for Petroleum & Energy Research-NIPER
ITT Research Institute P.O. Box 2128
Bartlesville, Oklahoma 74005
Telephone: 918-336-2400
Telefax: 918-336-2433

Dr. C.D. Scott
Senior Corporate Fellow
Oak Ridge National Laboratories
P.O. Box 2008
Oak Ridge, Tennessee 37831-6226
Telephone: 615-574-6775

Dr. K.D. Chapatwala
Chairman of Division of Natural Science
Selma University
1501 Lapsley Street
Selma, Alabama 36701
Telephone: 205-872-4599

Dr. W.R. Finnerty
Vice President - Research and Development
SURAX Inc.
P.O. Box 13301
Research Triangle Park
North Carolina 27709-3301
Telephone: 919-549-8650

Mr. G. Abbo
Senior Vice-P esident
Synergen Inc.
1885 - 33rd. Street
Boulder, Colorado 80302
Telephone: 303-938-6266
Telefax: 303-938-6270

Dr. E.C. Clausen
Professor
Department of Chemical Engineering
University of Arkansas
3202 Bell Engineering Centre
Fayetteville, Arkansas 72701
Telephone: 501-575-4951

Dr. J.L. Gaddy
Distinguished Professor and Head
University of Arkansas
Department of Chemical Engineering
3202 Bell Engineering Centre
Fayetteville, Arkansas 72701
Telephone: 501-575-4951
Telefax: 501-575-4346

Dr. M.J. McInerney
Associate Professor
Department of Botany and Microbiology
University of Oklahoma
770 Van Vleet Oval
Norman, Oklahoma 73072
Telephone: 405-325-6050

Dr. L.E. Patras
Research Biologist
Science and Technology Division
Unocal Corporation
376 South Valencia
Brea, California 92621
Telephone: 714-528-7201
Telefax: 714-528-7201

UNITED KINGDOM

Dr. V. Moses
Professor of Microbiology
School of Biological Sciences
Queen Mary College
and
Archaeus Ltd.
Mile End Road
London E1 4NS
Telephone: 44-1-975-5290
Telefax: 44-1-981-7517

NETHERLANDS

Dr. P. Bos
Department of Microbiology and Enzymology
Delft University of Technology
Julianalaan 67, 2628 BC
Delft
Telephone: 015-782359 or 782416

APPENDIX B

LIST OF PHASE II SURVEY PARTICIPANTS

(Industrial Technology Needs Assessment)

CANADA

Environmental Planning
Alberta Oil Sands Technology and Research Organization
500 Highfield Place
10010-106th Street
Edmonton, Alberta, T5J 3L8

Dr. S. Singh
Research Officer
Oils Sands and Hydrocarbon Recovery Department
Alberta Research Council
P.O. Box 8330, Station F
Edmonton, Alberta, T6H 5X2
Telephone: 403-464-9275
Telefax: 403-467-6784

Mr. J. Overall
Director of Research
Canadian Gas Research Institute
55 Scarsdale Road
Don Mills, Ontario, M3B 2R3

Mr. R.E. Wyman
Director of Research
Canadian Hunter Exploration Ltd.
435-4th Avenue S.W.
Calgary, Alberta, T2P 3A8
Telephone: 403-260-1718
Telefax: 403-260-1899

Mr. J.C. Campbell
Senior Research Engineer
Cape Breton Development Corporation
Mail Address:
P.O. Box 2500
Sydney, Nova Scotia, B1P 6K9
Street Adrress:
95 Union Street
Glace Bay
Nova Scotia, B1A 2P6
Telephone: 902-564-2848
Telefax: 902-564-2589

Mr. S. Hunter
Manager of Industry and Government Affairs
The Coal Association of Canada
502-205 9th Avenue S.E.
Calgary, Alberta, T2G 0R3
Telephone: 403-262-1544
Telefax: 403-265-7604

Mr. H.G. Rushton
Vice-President of Development
Crows Nest Resources Ltd.
Box 2699, Station M
Calgary, Alberta, T2P 3Y9
Telephone: 403-233-4355
Telefax: 403-232-4494

Dr. R.E. Overfield
Research Supervisor
Esso Resources Canada Limited
339 50th Avenue S.E.
Calgary, Alberta, T2G 2B3
Telephone: 403-259-0294
Telefax: 403-259-0649

Mr. C. McKenny
Chief Geologist
Fording Coal Limited
200-205 9th Avenue S.E.
Calgary, Alberta, T2G 0R4
Telephone: 403-264-1063
Telefax: 403-264-7339

Mr. A. Riopel
Advisor
Gaz Metropolitain Inc., DATECH Group
1717 Du Havre St.
Montreal, P.Q., H2K 2X3
Telephone: 514-598-3779
Telefax: 514-598-3461

Mr. R.M. Shanemar
Manager of Administration
Gregg River Resources Ltd./Monalta Coal Ltd.
840-6th Ave. S.W., 6th Floor
P.O. Box 2880
Calgary, Alberta, T2P 2M7
Telephone: 403-294-5077
Telefax: 403-294-5060

Mr. J.K. Jackson
Manager, Public Affairs
Home Oil Company Limited
(Subsidiary of Interhome Energy Inc.)
1700 Home Oil Tower, 324-8th Avenue S.W.
Calgary, Alberta, T2P 2Z5
Telephone: 403-232-7100
Telefax: 403-232-7678

Interprovincial Pipe Line Co.
(Subsidiary of Interhome Energy Inc.)
IPL Tower, 10201 Jasper Ave.
Edmonton, Alberta, T5J 2J9
Teiephone: 403-420-5145
Telefax:

Mr. A.C. Eastly
Executive Vice-President and Chief Operating Officer
Mark Resources Inc.
1000, 800-5th Avenue S.W.
Calgary, Alberta, T2P 4A4
Telephone: 403-267-1500
Telefax: 403-269-2297

Mr. T. Bourbonnie
Vice-President
Newalta Corporation
400, 333-11th Avenue S.W.
Calgary, Alberta, T2R 1L9
Telephone: 403-266-6556
Telefax: 403-265-9034

Mr. J.M. Gregory
Supervising Engineer, Utilization and Standards
Northwestern Utilities Limited
10035-105th Street
Edmonton, Alberta, T5J 2V6
Telephone: 403-420-7587
Telefax: 403-420-7400

Mr. G. Pangracs
Manager Mine Services
OBED Mountain Coal Company
Bagservile 7600
Hinton, Alberta, T0E 1B0
Telephone: 403-865-7600
Telefax: 403-865-8630

Phillips Petroleum Resources Ltd.
Suite 2800, SunLife Plaza
144-4th Avenue S.W.
Calgary, Alberta, T2P 3N4
Telephone:
Telefax:

Mr. P.E. Pinnington
President
Ontario Natural Gas Association
77 Bloor St. W., Suite 104
Toronto, Ontario, M5S 1M2
Telephone: 416-961-2339
Telefax:

Mr. R. Smitshoeh
Exploitation Supervisor
Renaissance Energy Ltd.
Suite 2500, 801-6th Avenue S.W.
Calgary, Alberta, T2P 3W2
Telephone:
Telefax:

Mr. J. Hutchinson
Director, Petroleum Division
Saskatchewan Research Council
515 Henderson Drive
Regina, Saskatchewan, S4N 5X1
Telephone: 306-787-9401
Telefax: 306-787-8811

Mr. D. Gill
Senior Staff Analyst
Shell Canada Limited
400, 4th Avenue S.W.
Calgary, Alberta, T2P 2H5
Telephone: 403-232-4832
Telefax: 403-232-4183

Mr. A. Johnson
Manager, Business Development
Sheridan Technical Associates Inc.
333 Wyecroft Road, Unit 6
Oakville, Ontario, L6K 2H2
Telephone: 416-338-0777
Telefax: 416-845-3413

Mr. S.C. Pick
Vice-President and Corporate Secretary
Smoky River Coal Limited
Suite 3380, West Tower, Petro-Canada Centre
150 - 6th Avenue S.W.
Calgary, Alberta, T2P 3Y7
Telephone: 403-266-4511
Telefax: 403-266-5193

Dr. J. Liu
Manager - Technical Services
Syncrude Canada Ltd.
10120-17th St., P.O. Box 5790, Station L
Edmonton, Alberta, T6C 4G3
Telephone:403-464-8523
Telefax:403-464-8405

UNITED STATES

Mr. H.E. Lebowitz
Manager, Fuel Science Program
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94303
Telephone: 415-855-2517
Telefax: